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TREATABILITY STUDY/ FOCUSED FEASIBILITY STUDY

Building 735 Site, Grissom AFB, Indiana
Air Force Center for Environmental Excellence (AFCEE)

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Appendix B:	Test Methods
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Appendix D:	Slug Test Data and Results
Appendix E:	Baseline Exposure Assessment Procedures
Appendix F:	SPL Environmental Laboratory Reports (not included with this submittal)

1.0 EXECUTIVE SUMMARY

Naturally occurring contaminant attenuation processes such as advection, dispersion, aerobic biodegradation, and anaerobic biodegradation can significantly enhance the rate of organic mass removal from contaminated groundwater aquifers. The Air Force and EPA are currently collaborating to research natural attenuation processes and develop natural attenuation as an effective remedial alternative for appropriate sites.

At the Building 735 site at Grissom AFB, data from site investigations (Section 2) was used to conduct a natural attenuation **Treatability Study** (Section 3) that included special field sampling and analysis and groundwater modeling components. The results from this study were used to perform a baseline exposure assessment and **Risk Assessment** for the site (Section 4). Finally, all of these data were used to prepare a **Focused Feasibility Study** (Section 5) that evaluated three remediation alternatives for the site: 1) natural attenuation with institutional controls, 2) natural attenuation combined with continued operation of an existing bioventing/air sparging system; and 3) installation of an aquifer dewatering/soil vapor extraction system.

1.1 Site Characterization Results

Two main hydrogeologic units are associated with the Bldg. 735 site: the shallower Wisconsin till, approximately 60 ft of unconsolidated glacial deposits composed of clay, silt, and sand; and a deeper fractured bedrock, consisting of limestone, dolomite, and shale. The hydraulic conductivity of the Wisconsin till unit is relatively low, contributing to estimated groundwater seepage velocities of ~6 ft/yr.

The sampling program identified the presence of BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) in unsaturated soils, saturated soils, and shallow groundwater at the site. The concentrations were relatively low: a maximum of 0.268 mg/L BTEX in groundwater and 195 mg/kg BTEX in soil. The area of the affected soil zone was approximately 265 x 65 ft, compared to a smaller dissolved plume area of 140 ft x 90 ft. Most of the contaminants were observed within the top 15 ft of the Wisconsin till, and no contaminants are considered to have migrated to the fractured bedrock.

- **Summary Point:**

BTEX-containing soils and groundwater were delineated, with the data showing concentrations to be relatively low and diffuse throughout the site. Groundwater moves very slowly through the contaminated zone (i.e., ~6 ft/yr) due to the low hydraulic conductivity of the silty clay/clayey silt till unit.

1.2 Treatability Study Results

Several key indicators demonstrated that vigorous natural attenuation processes are acting on the groundwater plume at the site (see Figure 1.1). As shown in the supporting data, key electron acceptors are depleted, metabolic by-products have accumulated in the plume area, elevated microbial populations were observed in the affected soils, and BIOPLUME biodegradation modeling is consistent with active aerobic and anaerobic natural attenuation processes. These indicators verify that the site contaminants are being removed by in-situ biodegradation.

Once active biodegradation processes were confirmed, a modified BIOPLUME biodegradation model was used to: 1) assess the risks associated with groundwater exposure pathways (described below) and 2) project the time required for the plume to dissipate. Although the biodegradation potential of the surrounding groundwater is high, seepage velocity is relatively slow at this site (~6 ft/yr). Therefore, the model projected that 10-25 years would be required for natural attenuation to completely remediate the plume.

Analysis of the effect of an active combined bioventing/air sparging system installed in late 1993 revealed that while the bioventing system is removing BTEX from the unsaturated soils, the data addressing the potential effect of the air sparging system on groundwater remediation are conflicting.

A companion vertical migration study indicated that natural attenuation and dispersion prevent the migration of measurable concentrations of BTEX compounds to the base drinking water wells screened in the deeper fractured bedrock unit.

- **Summary Point:**

Aerobic and anaerobic natural attenuation processes are very active in the groundwater at the Bldg. 735 site as shown by several indicators (see Figure 1.1). A modified BIOPLUME model indicates that complete plume remediation may take 10-25 years. The modeling also indicated that natural processes prevent migration of measurable BTEX compounds to the base drinking water wells screened in the deeper bedrock unit.

1.3 Risk Assessment Results

The baseline exposure assessment identified a number of potential exposure pathways associated with contaminated surface soils, unsaturated subsurface soils, and groundwater (see Figure 1.2). Because of the relatively low concentrations of site contaminants and the active natural attenuation processes, the risk assessment identified only one potential pathway that exceeded the risk goals: exposure to benzene from handling contaminated soils during construction activities. The risks associated with all other air, groundwater, and surface water pathways meet risk goals used in this study (i.e., $< 1 \times 10^{-6}$ increased carcinogenic risk and hazard quotient < 1).

Under a scenario of no institutional controls over construction work in the area, a cleanup standard of 9.2 mg/kg benzene in unsaturated soils was established. However, if a health and safety plan is required when working with benzene-contaminated soils (typically consisting of vapor monitoring and appropriate personal protective equipment), then an alternate soil cleanup standard of 60 mg/kg was calculated. This alternate cleanup level was not exceeded in any soils sampled at the site during the November, 1994 field program.

- **Summary Point:**

The BTEX compounds in groundwater and soil pose low risk to potential receptors exposed to site constituents migrating along various air, groundwater, soil, and surface water pathways (see Figure 1.2). The highest risk was calculated for construction workers exposed to benzene in contaminated soils. If a health and safety plan addressing benzene-contaminated soils is always mandated for the site for construction activities, the risk to construction workers is controlled and all of the groundwater and soils at the site fall below risk-based cleanup levels.

1.4 Focused Feasibility Study Results

Remedial action objectives were developed based on the results of the risk assessment, and a series of 12 remediation technologies were screened for

suitability of use at the site. Based on the screening, three remediation alternatives were retained:

REMEDIAL ALTERNATIVE	
1.	<i>Natural Attenuation of Groundwater and Institutional Controls for Soil</i>
2.	<i>Natural Attenuation of Groundwater and Continued Operation of Existing Bioventing/Air Sparging System</i>
3.	<i>Aquifer Dewatering/Soil Vapor Extraction System for Remediation of Affected Groundwater and Soils</i>

These alternatives were evaluated using the criteria for Feasibility Studies: overall protection of human health and the environment; compliance with existing regulations; long-term effectiveness and permanence; reduction of toxicity, mobility, or volume; short-term effectiveness; implementability; and cost.

An engineering cost analysis provided the following life-cycle costs (capital + O&M), with all costs expressed in net present value (1995 dollars).

- Alternative 1 Life-Cycle Cost: \$165,000
- Alternative 2 Life-Cycle Cost: \$230,000
- Alternative 3 Life-Cycle Cost: \$830,000

The comparison indicated that Alternative 1 and Alternative 2 had the same ranking, with Alternative 3 producing a lower ranking because of lower implementability and higher cost (see Table 1.1). While Alternative 2 had slightly higher costs, the bioventing system's ability to speed up remediation of soils gave this option better short-term effectiveness. When considering groundwater alone, Alternative 1 and Alternative 2 were assumed to have the same effectiveness because of questions about the effectiveness of the air sparging system for groundwater remediation.

• **Summary Point:**

Twelve remediation technologies were evaluated and used to develop three remediation alternatives that were analyzed in detail. Natural attenuation was a key component in the two alternatives that ranked the highest: Alternative 1: Natural attenuation with institutional controls and Alternative 2: Natural attenuation and continued operation of an existing bioventing/air sparging system. The third option, aquifer dewatering/soil vapor extraction, was projected to have shorter cleanup times but much higher cost.

2.0 SITE DESCRIPTION

2.1 Site Description and Hydrogeology

2.1.1 Site Background and Previous Investigations

Grissom Air Force Base (AFB) is situated 1.5 miles west of Bunker Hill in western Miami and eastern Cass Counties, Indiana. It is 11.5 miles north of Kokomo and 55 miles north of Indianapolis.

Grissom AFB was activated in 1943 as Bunker Hill Naval Air Station. Following the Second World War, the base was deactivated in 1946 and the land reverted to agricultural use. The base was reactivated in 1954, and in 1957 the 305th Air Refueling Squadron was moved to the base. As part of the base realignment program, Grissom AFB was converted to an Air Force Reserve base in October 1994. The base currently provides in-flight training for U. S. Air Force global air refueling services.

The Building 735 site is a secondary fuel storage and transfer facility. It is situated 200 feet south of the central operational apron and 800 feet north of the northeast-southwest runway (see Figure 2.1). The facility consists of a 2500 sq. foot building housing a control room and pump systems, eight 50,000 gallon underground storage tanks (USTs), and one 2000 gallon underground waste JP-4 tank, also called the slop tank (see Figure 2.2). Jet fuel is transferred from the above ground storage tanks on the north side of the base to the Bldg. 735 facility and stored until needed for aircraft refueling. Fuel is transferred to and from the facility via two 10-inch and one 6-inch diameter buried pipelines which exit on the east side of the building. The slop tank receives tank overfill product and wash water from the floor drains within the pump room.

The Bldg. 735 site is situated on a topographically flat area surrounded by taxiways and runways. Surface runoff is channeled through two south-flowing 1 ft deep drainage ditches which empty into an east-west oriented 7 ft deep perennial drainage ditch 210 ft south of Bldg. 735 (see Figure 2.2).

Previous soil and groundwater investigations at the Bldg. 735 site have focused on the area generally southeast of the building, where fuel was discovered seeping from beneath the building slab on February 13, 1991. Periodically, similar releases have been observed by US Air Force personnel in this vicinity over the previous 17 years. In 1991, six groundwater test wells were installed in the area of the release for the purposes of determining the extent of the affected

groundwater and for free product recovery (see Figure 2.2). Approximately 30 cubic yards of contaminated soil were also excavated from the site in conjunction with the free product removal. In February 1991, a leak in UST No. 3 was identified and the tank was subsequently removed from service. During November 1991, 12 soil borings were drilled at the Bldg. 735 site with four of the borings being converted to groundwater monitoring wells. In 1993 an air sparging system consisting of 8 vent/air sparging wells and 5 vapor monitoring points was installed generally east and southeast of Bldg. 735. The system is currently in operation.

2.1.2 Regional Hydrogeology

Published geologic and hydrogeologic data, site information obtained during previous site investigations, and information from interviews with base personnel during the current investigation have been compiled to define the general physiographic setting, regional stratigraphy, and groundwater conditions beneath the Bldg. 735 site. Water well records, including driller's logs and well completion reports, were obtained from the Indiana Division of Water Resources for 19 fresh water supply wells located on the base and in adjacent areas. The following is a summary of regional hydrogeologic site conditions based on review of the available information.

Grissom AFB is situated in the Tipton Till Plains section of the Central Lowland physiographic province. This section consists of wide flat till plains overlying glacial ground moraine deposits. The base is situated on a till plain about 1 mile west of the north-trending Union City moraine. Relief across the base is approximately 30 feet with surface elevations ranging from 780 to 810 feet above mean sea level. Surface runoff from the base is channeled through drainage ditches which discharge into Deer Creek to the west or Pipe Creek to the north, both of which are tributaries of the Wabash River. Average annual precipitation at Grissom AFB is 36.6 inches, and the mean monthly temperature is approximately 40°F in the winter and approximately 65°F in the summer. The mean annual evaporation is 32 inches (Environmental Science and Engineering, 1994).

Soil surveys conducted have classified the soils at the base as Treaty or Fincastle silt loams (Miami and Cass County Soil Surveys, 1981 and 1979, respectively). Both soil types have high available water capacity, low to moderate permeability, and are generally poorly drained. Most of the land outside of the base with these soil types is used for farming.

In the vicinity of the base, two principal stratigraphic units are found: 1) a near-surface glacial fine-grained till, with alluvial sand and gravel at its base, and 2) carbonate and shale bedrock. Unconsolidated glacial till deposited as ground moraine during the Pleistocene Wisconsinan Stage of ice advance extend from the surface to an average depth of 60 ft. The till consists of unstratified yellowish brown and gray sandy clay and clayey silt. Scattered thin sand and gravel units of limited lateral extent occur within the till and typically contain high amounts of clay. Thickness of the sand and gravel zones range from 0.5 ft to 4.5 ft. The glacial till does not generally yield water in sufficient quantities to be used for domestic or municipal supply.

An alluvial sand and gravel unit occurs at the base of the Wisconsinan Till directly above the Paleozoic bedrock at depths of 45 ft to 70 ft below ground surface and represents alluvium deposited along preglacial streams (Thornbury and Deane, 1955). The unit is about 2.0 ft to 5.0 ft thick and consists of coarse grained poorly graded sand, and fine gravel. The alluvial sand and gravel yields water in sufficient quantities to supply domestic and municipal supply wells in the area including the Grissom AFB water supply wells. The unit is typically combined with the underlying fractured limestone in well screen intervals.

The bedrock in the Grissom AFB area consists of more than 150 feet of fractured Devonian and Silurian limestone, dolomite, and shale. The upper surface of the bedrock is uneven due to weathering and erosion prior to burial under the glacial sediments, and dips to the west and northwest in the area of the base as mapped by Bruns *et al.* (1985). The upper 10 ft to 20 ft of the limestone, which is more than 100 ft in thickness, is weathered and fractured. The limestone bedrock serves as the primary fresh water aquifer for domestic and municipal supply wells in the vicinity of Grissom AFB. Well yields from the bedrock have been up to 990 gpm.

Fresh water for Grissom AFB is obtained from 8 wells which are screened in the upper part of the fractured bedrock. There are currently 4 wells which supply water to the base water plant, one well provides water for the base golf course, two wells supply water to the control tower, and one well provides water to the jet engine test cell. The well locations, completion details and well use are discussed in Section 3.6 of this report.

2.1.3 Site Stratigraphy of Shallow Soils

The characterization of shallow soils underlying the Bldg. 735 site is based on review of existing data from previous studies and on soil descriptions from 10

monitoring wells and 4 soil borings drilled during this investigation (see Appendix B).

These data indicate that the shallow subsurface at the Bldg. 735 site consists of unstratified glacial till composed of sandy clay and clayey silt, with thin, laterally discontinuous, coarser-grained zones. Plastic clay units, which might serve as impermeable confining layers, were not encountered within the upper shallow soils at this site. The stratigraphy at the site is shown on a fence diagram (see Figure 2.3) and on two cross sections (see Figure 2.4). The upper 15 ft of these tills can be divided into roughly two units, based on color, composition, and texture, as follows:

- 1) **Mixed Clayey Silt and Silty Clay** - A silty clay and clayey silt unit occurs from the surface to a depth of about 7.0 ft BGS. The clayey silt which is yellowish brown and includes occasional sand pockets and scattered pea gravel was encountered in borings MW-9 west of Bldg. 735 and in borings south and east of the building (see Figure 2.3). Gray silty clay occurs west and southwest of the building (see MW-3 and SB-7). The top of the saturated zone was encountered within this unit.
- 2) **Gray Silty and Sandy Clay** - Gray silty and sandy clay occurs at the site from a depth of about 7.0 ft to the maximum boring depth of 15.0 ft at all locations (except well MW-10). The clay contains scattered pea gravel and cobbles and occasionally thin sand lenses. The upper 2 ft of this unit (approximately 7 ft to 9 ft BGS) consists of hard, dense, silty clay with calcareous nodules. Groundwater seepage from the sand lenses in this zone was noted while drilling.

Monitoring well MW-10 encountered this clay unit to its maximum depth of 30 ft BGS. However, within this interval a 3.5 ft thick unit of well graded gravelly sand was encountered from a depth of 21.0 ft to 24.5 ft BGS.

2.1.4 Site Hydrogeology

The mixed clayey silt and silty clay unit underlying the Bldg. 735 site from the ground surface to a depth of 7.0 ft (Unit 1 above) represents the uppermost water-bearing unit beneath this site. A total of 13 groundwater monitoring wells have been installed in this unit and the uppermost part of Unit 2 (see Table 2.1). One well (i.e., MW-10) was screened within a deeper sand in Unit 2, above.

The depth to groundwater is relatively shallow at the site. Static water levels measured on November 16, 1994 ranged from 3.4 ft to 7.3 ft below the ground surface, indicating unconfined conditions. The groundwater levels in the immediate vicinity of Bldg. 735 have been measured as high as 1.3 ft BGS at well GMW-2 in previous investigations (TCT, 1992). During the summer months the depth to groundwater increases to 6.0 ft to 9.0 ft BGS (Engineering-Science, 1993).

The shallow groundwater is recharged by infiltration of rainfall and snow melt from the ground surface. Static water level measurements suggest that discharge from the shallow groundwater to the adjacent drainage ditch is taking place. The potentiometric surface contour map, based on static water levels measured on November 16, 1994 indicates that groundwater within the mixed silt and clay unit is generally moving in a southerly direction, at an average lateral hydraulic flow gradient of 0.012 ft/ft (see Figure 2.5).

To test the hydraulic characteristics of the upper water-bearing unit at the site, falling-head and rising-head slug tests were performed at 5 monitoring well locations. Four of the monitoring wells (i.e., MW-1, MW-3, MW-8, and MW-9) were screened in a shallow horizon from depths of 4.3 ft to 13.8 ft BGS, and one monitoring well (MW-10) was screened in a deeper interval from 19.3 ft to 28.8 ft BGS. The results of slug test calculations indicate an average hydraulic conductivity of 5.6×10^{-5} cm/sec for the shallow screened interval, and of 2.3×10^{-4} cm/sec for the well screened in the deeper horizon. The average hydraulic conductivity calculated for well MW-1, which is situated within the hydrocarbon plume area, was 9.6×10^{-5} cm/sec.

Based on the hydraulic conductivity for well MW-1, a hydraulic gradient of 0.012 ft/ft and an assumed porosity of 20 percent, the calculated seepage velocity within the water-bearing unit is 6 ft/yr. A summary of the results of slug test calculations is shown on Table 2.2; slug test field data is included in Appendix D.

A preferential groundwater flow path to the south along the eastern portion of the Bldg. 735 site is indicated by: 1) slightly higher hydraulic conductivity along the east side of the building (i.e., a hydraulic conductivity of 6.8×10^{-5} cm/sec vs. 4.3×10^{-5} cm/sec), and 2) the presence of coarser grained soils (i.e., clayey silt and sand) along the east side of the building (see Figure 2.3).

2.2 Distribution of Contaminants

2.2.1 Affected Soil Conditions

Soils from a total of 10 soil borings and 4 monitoring wells were sampled from ground surface to depths of up to 30 ft in the vicinity of Bldg. 735 during October 1994. Sampling procedures and criteria for selection of samples for laboratory analysis are discussed in Appendix B of this document. Results of laboratory analyses of soil samples from the borings are shown in Tables 2.3 and 2.4, and on Figure 2.6. Original laboratory reports for soil analyses are included as Appendix F.

Based on this sampling, a zone of affected soils approximately 250 ft by 165 ft and up to 30 ft deep was delineated. Benzene, toluene, ethylbenzene, and xylenes (BTEX) were detected in samples from depths of 1.5 ft to 30 ft from soil borings south and southeast of Bldg. 735, and in soils from well MW-3, northwest of the building. Contaminant concentrations in soils generally decreased with increasing depth with the highest concentrations (i.e., >0.1 mg/kg) found in the 1.5 ft to 7.5 interval below ground surface. The maximum detected concentrations of benzene (23.5 mg/kg), toluene (50 mg/kg), and xylenes (96 mg/kg) were measured at a depth of 6.0 feet below grade in boring SB-10, and the maximum concentration of ethylbenzene (28 mg/kg) was measured at a depth of 3.0 ft below grade in soils tested from well MW-2 (see Table 2.3). In soils from well MW-10, low levels of BTEX (0.082 mg/kg) were found at a depth of 30 ft below ground surface.

The maximum total petroleum hydrocarbons (TPH) concentration detected in the soil was 4300 mg/kg from a depth of 2.0 feet below grade at boring location SB-10. No lead was detected above the specified detection limit at any location. A field test indicated the presence of residual (non-mobile) non-aqueous phase liquids (NAPLs) at depths of 4 ft to 8 ft below ground surface at boring SB-10, southeast of the Slop Tank.

Two background soil samples from the saturated zone were analyzed to determine representative background organic carbon values for use in adsorption calculations. The results, 0.20% and 0.29% in wells MW-3 and MW-9, respectively, indicated a moderate potential for adsorption of dissolved constituents moving through clean soils.

Twelve samples were analyzed for total microorganism count (see Table 2.5). All wells, except for MW-9 located west of the Bldg. 735 site, confirmed the presence of microbial populations. The highest populations were measured at SB-6, SB-7, SB-4, MW-6, MW-1, and MW-7, all located within the affected soils area. Samples collected from outside the affected soils area measured much lower numbers of microbial colonies (i.e., <2,100 colony forming units per gram).

2.2.2 Affected Groundwater Conditions

A total of 10 new Wisconsinan monitoring wells were installed as part of this program. The nine shallow wells (MW-1 through MW-9) were screened from 4.3 ft to 13.8 ft below ground surface, and the deep well (MW-10) was screened from 19.3 ft to 28.8 ft below ground surface within the shallow clayey silt/silty clay till. Monitoring well installation and sampling procedures are discussed in Appendix B of this document. The new wells and 4 existing monitoring wells (i.e., GMW-1,

2, 3, and 4) were sampled during November 1994. Laboratory test results are shown on Tables 2.6 - 2.8, and Figure 2.7, field parameter measurements are presented on Table 2.9. Well construction specifications are provided on Table 2.1. Original laboratory reports for groundwater analyses are included as Appendix F.

Although field gas chromatograph readings indicated a large plume area, more accurate laboratory sample results indicated only two of the wells contained BTEX constituents at detectable concentrations. Benzene levels of 0.056 mg/L and 0.250 mg/L, ethylbenzene levels of 0.019 mg/L and 0.008 mg/L, and xylene levels of 0.089 mg/L and 0.010 mg/L were observed in monitoring wells MW-1 and GMW-3, respectively. Toluene was detected in monitoring well MW-1 at a concentration of 0.023 mg/L.

TPH was detected in groundwater at levels of 0.63 mg/L and 1.10 mg/L in monitoring wells MW-1 and GMW-3, respectively (see Table 2.6). The trimethylbenzenes were not detected above the specified detection limit in any of the monitoring wells tested (see Section 3.4).

Laboratory results of groundwater testing for inorganic compounds indicated lead was not detected in any of the wells (see Table 2.7). Significant depletion of some electron acceptors (oxygen and sulfate) and generation of metabolic by-products (ferrous iron and methane) indicate active natural attenuation processes. These data are discussed in detail in Section 3.4.

Based on the results of laboratory groundwater analyses, the extent of affected groundwater is estimated to be approximately 140 ft long by 90 ft wide, or 9,700 ft² (see Figure 2.7). The plume thickness, which is based on the screened interval for the monitoring wells, approximately 10 ft, and a porosity of 0.20 have been used to calculate the affected groundwater volume as approximately 145,000 gallons.

2.2.3 Estimated Mass of Contaminants in Groundwater and Soil

Groundwater and soil sampling results were used to estimate the distribution of BTEX compounds in the dissolved phase and in the soil at the site. To estimate the total BTEX mass on all of the unsaturated and saturated soils, the sampling data was divided into depth intervals and concentration contours were drawn across the affected soil area. This approach yielded a total mass estimate of 79,200 grams of BTEX material in the affected soils at the Bldg. 735 site (see Table 2.10), or about 175 pounds.

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A separate analysis was performed for the groundwater plume area. Estimated groundwater concentration contours were used to calculate the total mass of dissolved BTEX at the site. In addition, the mass of BTEX on the soil in contact with affected groundwater was estimated by contouring only soil data from the zone between 5 and 15 ft BGS, the approximate depth of the contaminated groundwater. Using this approach, the total mass in the dissolved phase was estimated to be 126 grams, whereas BTEX in the saturated soils in equilibrium with the plume was calculated to be 5,900 grams. This low ratio of dissolved to soil BTEX indicates that BTEX in the soil is not typical for adsorption of organics from a moving dissolved phase plume, where ratios of 1:1 are typical (retardation factor of 2). Rather, the soil in the plume appears to contain residual contamination from the original spill event or events that is serving as a long-term source of BTEX to groundwater (see Section 3.5).

TABLE 2.8
RESULTS OF GROUNDWATER TESTING:
HEADSPACE METHANE, ETHANE, ETHENE, AND CARBON DIOXIDE

Treatability Study/Focused Feasibility Study
 Building 735 Site, Grissom AFB, Indiana

SAMPLE LOCATION:	MW1	MW2	MW3	MW4	MW5	MW6	Duplicate MW6	MW7
SAMPLING DATE:	11/16/94	11/16/94	11/17/94	11/17/94	11/16/94	11/17/94	11/17/94	11/17/94
ANALYSIS DATE:	11/21-11/22/94	11/21-11/22/94	11/22/94	11/22/94	11/21-11/22/94	11/22/94	11/23/94	11/22/94
COMPOUND	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Methane	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Ethene (Ethylene)	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32
Ethane	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Carbon Dioxide (ppm)	26	21	24	27	22	33	29	46

SAMPLE LOCATION:	Duplicate MW7	MW8	MW9	MW10	GMW1	GMW2	GMW3	GMW4
SAMPLING DATE:	11/17/94	11/17/94	11/16/94	11/17/94	11/18/94	11/17/94	11/17/94	11/18/94
ANALYSIS DATE:	11/23/94	11/23/94	11/21-11/22/94	11/23/94	11/23/94	11/23/94	11/22/94	11/23/94
COMPOUND	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Methane	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	1.8	<0.12
Ethene (Ethylene)	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32
Ethane	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Carbon Dioxide (ppm)	40	28	16	10	29	24	68	31

NOTES:

1. Groundwater samples collected at locations shown on Figure 2.2.
2. All analyses performed by SPL Environmental Laboratories, Houston, Texas, in accordance with R.S. Kerr Environmental Research Laboratory Standard Operating Procedure (RSKSOP) 114.
3. MW-6 and MW-7 duplicate samples were submitted to laboratory as samples MW-66 and MW-77, respectively.
4. < = Compound not detected above the specified detection limit

3.0 NATURAL ATTENUATION TREATABILITY STUDY

3.1 Test Objectives

The natural attenuation (intrinsic remediation) approach attempts to verify and then quantify the rate of natural destruction of organic contaminants in the subsurface to determine if this rate is sufficient to protect human health and the environment at a particular site. Evaluation of natural attenuation as a remediation option involves three tasks:

1. *Collect hydrogeologic and water quality data using the Air Force/EPA Natural Attenuation protocol (summarized in Section 2).*
2. *Analyze the data to determine if the observed groundwater plume shape and the distribution of electron acceptors and by-products indicate significant biological activity in the aquifer.*
3. *Determine if natural attenuation computer models can explain the observed distribution of contaminants, electron acceptors and by-products. If so, apply the models to estimate the extent of further plume migration and the time required to completely degrade the contaminants. In addition, apply the models to estimate the risk to potential receptors and the resulting potential risk-based cleanup standards for the source zone.*

This section summarizes the results of Steps 2 and 3 as applied to data obtained from the Bldg. 735 site. Section 3.4 reviews the observed plume shape and the distribution of electron acceptors and by-products at the site. Section 3.5 summarizes results from applying a natural attenuation model to this site.

3.2 Introduction to Natural Attenuation

During the past ten years, natural in-situ biodegradation in the contaminant transport process has been the focus of increasing attention. Numerous studies conducted by the EPA and other researchers have clearly demonstrated that natural in-situ biodegradation can effectively prevent the growth of groundwater contaminant plumes at many sites. Site parameters which have been identified as influencing the rate of in-situ biodegradation include background dissolved oxygen concentration, the presence of alternative electron acceptors, hydraulic conductivity, potentiometric gradient, contaminant concentrations, and the type of the contaminant or contaminant mixture. In general, natural in-situ biodegradation has been shown to be effective on a range of hydrocarbons, including benzene, toluene, ethylbenzene, and xylenes (BTEX), which comprise the major contaminants of concern at petroleum fuel sites.

At the same time that the role of natural biodegradation has become more widely recognized, additional information has come to light which indicates that the performance of numerous conventional pump-and-treat groundwater remediation systems have difficulty meeting site restoration goals. Hydrogeologic factors, such as aquifer heterogeneity and low permeability, can greatly hinder site cleanup. Contaminant characteristics, such as the presence of non-aqueous phase liquids (NAPLs), also can be a significant obstacle to meeting cleanup goals. Due to these limitations, the removal of contaminants to non-detectable or background concentrations using active remediation systems may be technically impracticable at many sites, particularly within typical design timeframes (i.e., 2-5 years).

Although rapid aquifer restoration may be impracticable with conventional active remediation systems at many sites, natural processes will eventually restore most aquifers to pre-spill conditions by biodegrading the dissolved organic constituents. If it can be shown that potential receptors are not exposed to hazardous levels of site constituents while natural attenuation is underway, then a strong case can be made to utilize natural attenuation (also called natural biodegradation or intrinsic bioremediation) as a remediation approach. A technically sound evaluation of how natural attenuation affects plume migration can eliminate the need for installation and operation of costly groundwater remediation systems. In addition, at sites where some intervention is needed, understanding and quantifying natural attenuation may minimize the requirements for extensive active remediation systems.

One key technical point regarding natural biodegradation processes is that only dissolved hydrocarbons are utilized. Hydrocarbons present either as free-phase NAPL (a mobile layer of fuel that can accumulate in monitoring wells) or as residual NAPL (tiny blobs of NAPL trapped in individual pores) cannot be directly consumed. However, natural biodegradation can accelerate the dissolution (leaching) of soluble components such as BTEX from the NAPL phase into groundwater and reduce the time required to remediate source zones. Therefore, natural attenuation treats groundwater contamination directly and rapidly, and treats soil/NAPL contamination indirectly, but more slowly.

To develop scientifically sound methods to verify and quantify the natural attenuation process, the Air Force Center for Environmental Excellence (AFCEE) and the EPA's R.S. Kerr Environmental Research Lab (RSKERL) have collaborated on an extensive research program focusing on natural attenuation processes. Over 40 natural attenuation field investigations have been conducted, are ongoing, or are planned by AFCEE. In addition, using guidance from Dr. John Wilson of the RSKERL, the Air Force and EPA have developed the

"Technical Protocol for Implementing the Intrinsic Remediation With Long-Term Monitoring Option for Natural Attenuation of Dissolved-Phase Fuel Contamination in Groundwater" (Wiedemeier *et al.*, 1994) which is now being used to conduct natural attenuation projects. Current research efforts are now focusing on building better natural attenuation models. This work, being conducted by GSI and Dr. Hanadi Rifai of Rice University, will make it easier to evaluate and quantify the rate of natural attenuation at petroleum fuel sites.

3.3 Experimental Design

This investigation was designed following the Air Force/EPA Technical Protocol (Wiedemeier *et al.*, 1994). The following tasks were performed:

- 1) Evaluated data generated during previous investigations in order to assess site conditions and the need for additional data.
- 2) Further defined physical site characteristics (e.g., site stratigraphy and hydrogeology) from soil boring and monitoring well data collected during this program.
- 3) Delineated contaminant concentrations in soil, including i) an estimate of the volumetric extent of affected soils containing free-phase or residual NAPLs (if present) and ii) development of concentration maps to illustrate the distribution of site constituents on soils.
- 4) Delineated and mapped the dissolved phase hydrocarbons and constituents associated with natural biodegradation reactions listed below:

Type of Reaction	Electron Acceptor	Metabolic By-Product
Aerobic	Oxygen	CO ₂
Anaerobic	Nitrate	N ₂ , CO ₂
Anaerobic	Ferric Iron (solid)	Ferrous Iron (dissolved)
Anaerobic	Sulfate	H ₂ S
Anaerobic	CO ₂	Methane

*Note: Constituents in **BOLD** were measured as part of the field study.*

As specified in the protocol, the actual electron acceptors for the aerobic reactions (oxygen), nitrate reduction (nitrate), and sulfate reduction (sulfate) were measured directly. Because of the difficulty in measuring ferric iron (found as a solid phase on the aquifer matrix) and the difficulty in interpreting carbon dioxide data (which is heavily influenced by alkalinity reactions), the metabolic by-products (ferrous iron and methane, respectively) are measured instead to assess iron reduction and methanogenic activity.

- 5) Verified that natural attenuation is occurring using the following criteria as evidence of on-going biological processes:
 - The dissolved hydrocarbon plume is stable or shrinking;
 - The areal extent of the dissolved phase hydrocarbon plume is less than would be predicted if no biodegradation was occurring;
 - Complete or partial depletion of measurable electron acceptors (oxygen, nitrate or sulfate) is observed in the dissolved hydrocarbon plume;
 - Metabolic by-products (ferrous iron and methane) are observed in the plume;
 - Microbial assays indicate the presence of active, heterotrophic bacteria in the plume area, particularly in mixing zones.
- 6) Applied natural attenuation models such as BIOPLUME and BIOSCREEN (see Appendix C) to estimate the maximum extent of dissolved hydrocarbon migration and to develop general estimates of the time required for natural attenuation to completely degrade the dissolved contaminant plume.
- 7) Prepared a baseline exposure assessment for groundwater to identify potential receptors and active groundwater pathways. Information from the baseline exposure assessment was then used with a natural attenuation model to estimate the risk posed to potential receptors and to estimate risk-based clean-up levels, if needed (see Section 4).

The results of the hydrogeologic site investigation are discussed in Section 2 of this TS/FFS report; laboratory test results supporting natural attenuation are discussed below. Results from Tasks 4 and 5 are summarized in Section 3.4, below, and modeling results (Tasks 6 and 7) are presented in Section 3.5.

3.4 Evidence of Natural Attenuation: Analysis of Monitoring Data

3.4.1 Plume Characteristics

Two methods were used to determine if the groundwater monitoring data indicated active natural attenuation:

Use of Organic "Tracers"

A dissolved hydrocarbon plume undergoing biodegradation will exhibit a different length and width than a plume comprised of a conservative (nonadsorbing and nonbiodegrading) constituent. At many municipal landfills, for example, the source zone leaches both dissolved hydrocarbons and conservative constituents, such as chloride, into groundwater. The dissolved hydrocarbon plume is almost always shorter and thinner than the chloride plume because the intensive biodegradation of dissolved hydrocarbon occurs along the fringes of the plume where dispersive mixing enhances degradation.

At petroleum fuel spills, however, mobile conservative constituents, such as chloride, are generally not released. Therefore the Air Force/EPA Natural Attenuation Protocol includes monitoring of alternative tracers that have the same mobility characteristics as benzene but do not biodegrade as readily. The extent of migration of these tracers, consisting of three trimethylbenzene compounds, are compared to the extent of benzene migration. If the travel distance and plume width for the trimethylbenzene constituents is greater than for the BTEX compounds, then natural attenuation is indicated.

At the Bldg. 735 site, the observed BTEX plume is limited in areal extent, with only two wells showing detectable dissolved hydrocarbons during the 1994 sampling event. No trimethylbenzenes were observed in any of the wells sampled, making this indicator of natural attenuation inconclusive.

Bldg. 735 Plume Over Time

Apparent changes in the dissolved hydrocarbon plume over time indicate that the plume is shrinking. As shown on Figure 2.6, the zone of saturated soils (deeper than 3-7 ft below grade) that contain BTEX extends far beyond the observed dissolved BTEX plume (see Figure 2.7). This indicates that: 1) natural biodegradation has removed the leached BTEX components from areas with slightly contaminated soils, and 2) the original fuel release once spread free-phase hydrocarbons over a relatively large area along the water table. This original release must have produced a dissolved BTEX plume that was once as large as the current extent of contaminated soil but has shrunk over the years to its current size due to natural attenuation (see Figure 3.1).

As shown on Figure 3.2, historical information was available for only four wells. These data, generated in 1991, were compared with the recent, 1994, data. The results from one well (GMW-3) with measurable BTEX concentrations during both sampling events (0.25 mg/L in 1991 vs. 0.268 mg/L in 1994) are consistent with a slowly shrinking plume and the modeling results (see Section 3.5). The slight change in concentration in GMW-3 is within laboratory analysis variability and suggests that no substantial plume growth is occurring.

• **Summary Point: BTEX Data**

Use of organic tracer data (trimethylbenzene compounds) did not confirm the occurrence of natural attenuation. However, areas with soils showing measurable BTEX concentrations, but no corresponding dissolved BTEX concentration, indicate that biodegradation processes are completely degrading BTEX that is leaching from slightly contaminated soils. These site characteristics provide indirect evidence of a shrinking BTEX plume since the original spill event (see Figure 3.1).

3.4.2 Electron Acceptor Consumption/By-Product Generation

Biodegradation of petroleum hydrocarbons is essentially an oxidation-reduction reaction where the hydrocarbon is oxidized and an electron acceptor is reduced. There are a number of different compounds that can act as electron acceptors including oxygen, nitrate, iron oxides (ferric iron), sulfate, and carbon dioxide. In addition, ferrous iron and methane are by-products of anaerobic biodegradation.

The following theoretical reactions represent biodegradation mechanisms (Borden, 1994), where the hydrocarbon substrate is assumed to be toluene, $C_6H_5-CH_3$. Reactants and by-products that are measured as part of the Air Force/EPA Natural Attenuation Field Protocol are shown in **BOLD**.

Biodegradation Process	Theoretical Reaction
Aerobic Degradation (Oxygen Reduction)	$C_6H_5-CH_3 + 9 O_2 \rightarrow 7 CO_2 + 4 H_2O + \text{Energy}$
Nitrate Reduction	$C_6H_5-CH_3 + 6 NO_3 \rightarrow 7 CO_2 + 4 H_2O + 3 N_2 + \text{Energy}$
Ferric Iron Reduction	$C_6H_5-CH_3 + 36 Fe(OH)_3 \rightarrow 7 CO_2 + 36 Fe^{+2} + 72 OH^- + 22 H_2O + \text{Energy}$
Sulfate Reduction	$C_6H_5-CH_3 + 4.5 SO_4^{=2} + 3 H_2O \rightarrow 2.25 H_2S + 2.25 HS^- + 7 HCO_3^- + 0.25 H^+ + \text{Energy}$
Methanogenesis	$C_6H_5-CH_3 + 5 H_2O \rightarrow 4.5 CH_4 + 2.5 CO_2 + \text{Energy}$

Using these reactions and data from groundwater samples, the following patterns can be applied to determine if natural attenuation is occurring at a site:

- Complete or partial depletion of measurable electron acceptors (oxygen, nitrate or sulfate) is observed in the dissolved hydrocarbon plume;

- Accumulation of metabolic by-products (ferrous iron and methane) are observed in the plume;

As shown on Figure 3.3, geochemical data indicate intense aerobic and anaerobic biodegradation is occurring in the dissolved groundwater plume at the Bldg. 735 site:

Supports Natural Attenuation?			Observed Pattern of Electron Acceptor/By-Products at Bldg. 735
Y	N	I	
√			Dissolved oxygen concentrations fall from background levels of over 10 mg/L outside of the plume area to approximately 3.4 mg/L inside the plume.
		√	Nitrate exhibits low background concentrations (0.8 mg/L), but shows some depletion in the general vicinity of the plume.
√			Depletion of sulfate is observed in the plume area, with a minimum concentration of 7 mg/L compared to background levels of over 80 mg/L.
√			Ferrous iron concentrations of 2.8 mg/L over the plume area were measured from a non-detect background condition.
√			Methane was measured in the area of highest groundwater contamination at 1.8 mg/L.

Note: Y = "Yes"; N = "No"; I = "Inconclusive"

As with most natural attenuation sites, the correlations between the observed dissolved hydrocarbon plume and the electron acceptors/by-products have some anomalies. The area to the west of the BTEX plume indicates relatively low levels of dissolved oxygen (4.2- 4.6 mg/L) while the areas to the north and south show high concentrations (> 9 mg/L). The plume area still has the lowest value at 3.4 mg/L at well GMW-3. One reason for the relatively high concentrations in the middle of the plume (many sites show < 0.1 mg/L) is the ongoing bioventing/air sparging system at the site; prior to system start-up, the observed dissolved oxygen concentrations were close to zero.

Interestingly, data from well GMW-3 indicate active on-going anaerobic biodegradation by sulfate reducers, iron reducers, and methanogens even with dissolved oxygen concentrations at non-anaerobic levels (> 1 mg/L). The most probable explanation is that the air sparging system affects only the shallower zones of the contaminant plume, and that the water samples collected from this

well (and other wells) represent a mixture of aerobic and anaerobic conditions (see Appendix C).

The site exhibits very low nitrate concentrations except for elevated and unexplained concentrations at two wells, GMW-1 and MW-7. The background concentrations for sulfate vary widely, from 46 mg/L at GMW-2 to over 100 mg/L at several wells. There is definite sulfate depletion, however, as well GMW-3 shows only 7 mg/L of sulfate.

The by-product data for ferrous iron and methane indicate strong correlations with the dissolved plume. The methane reading of 1.8 mg/L at monitoring well GMW-3 indicates that methanogens are active at this site, especially in the affected groundwater area. Methane concentrations, however, are somewhat lower than would be expected, probably due to increased concentration of dissolved oxygen from the ongoing bioventing/air sparging system at the site. Therefore, all the available oxygen, nitrate, ferric iron, and sulfate are quickly consumed in the plume area, and methanogens are contributing to the biodegradation processes at this site.

• **Summary Point: Electron Acceptors/Metabolic By-Products**

The distribution of dissolved oxygen, ferrous iron, sulfate, and methane confirm the presence of intense on-going biodegradation, both aerobic and anaerobic, at the site (see Figure 3.3).

3.4.3 Microbial Assays

Microbial assays were conducted on selected soil samples at the Bldg. 735 site. For this study, an Agar-Plate Method for enumerating heterotrophic microorganisms was used to indicate the relative population of microorganisms in the soil samples. These data, reported as colony-forming units per gram of sample (CFU/g), are generally used only in a qualitative sense because of the extreme variability in the data.

The results from the Bldg. 735 sampling indicate very active microbial populations in areas of the site with BTEX in the soil (see Table 2.5). The lowest population (no detect, or < 100 CFU/g) was observed from soil samples collected at MW-9, a relatively clean background area located far west of the site. The highest concentrations were observed in the fringe of the contaminated soil zone, at MW-6, SB-6, and SB-7. These results are consistent with observations of microbial populations at other sites: lower counts in background samples, highest populations in fringe zones.

• **Summary Point: Microbial Assays**

High populations of microorganisms were detected in soil samples containing BTEX, indicating on-going active biodegradation at the Bldg. 735 site. As expected at sites undergoing natural attenuation, clean background zones exhibited lower microbial counts than samples in contaminated areas.

3.5 Evidence of Natural Attenuation: Modeling Results

3.5.1 Conceptual Model of Bldg. 735 Site

The current site conceptual model assumes that spills of JP-4 occurred from the Bldg. 735 fuel storage/pumping facility, consisting of a 2500 square foot control/pump room, eight 50,000 gallon underground storage tanks, and one 2000 gallon underground waste slop tank. The first environmental investigation focused on a surface seep of JP-4, occurring in 1991, immediately southeast of the building (see Figure 3.2). One account indicates fuel spills and leaks date as far back as 1976 (ESE, 1993).

Initial remediation efforts included removal of 50 gallons of free product from 5 recovery wells in 1991, and excavation of 30 yd³ of contaminated soil from an area adjacent to the slop tank. In October 1993, an 8-well bioventing system was installed in a zone extending about 100 ft northwest and 100 ft southeast of the slop tank. The wells were installed with a screened interval extending 11 ft below grade, thereby inducing some air sparging of the saturated zone except during periods of low water levels. The system is currently in operation.

Site Hydrogeology

As described in Section 2, the Bldg. 735 site is located in a glaciated area consisting of widely spaced morainal ridges separated by low relief till plains. Two main hydrogeologic units are associated with the area: approximately 60 ft of unconsolidated glacial deposits composed of clay, silt, sand, and gravel, and fractured bedrock consisting of limestone, dolomite, and shale. Water supply in the area is typically taken from the fractured bedrock or from alluvial deposits in nearby buried valleys, the closest being the Teays Valley located about 10 miles to the north.

The local stratigraphy consists of the following units:

- Wisconsinan Till..... 45 - 70 ft thick
- Interbedded Silt and Sand Zones (In upper 30 ft) 0.5 - 7 ft thick

- Basal Sand and Gravel Zone (Above bedrock) 2 - 5 ft thick
- Fractured Limestone Bedrock 100+ ft thick

Site investigations have provided the following estimates of hydrogeologic properties of the Wisconsin till (also called the silty clay/clayey silt unit) aquifer in the area of the dissolved hydrocarbon plume:

- Typical static water level 1 - 5 ft below grade in winter
6 - 9 ft below grade in summer
- Hydraulic Conductivity 5×10^{-5} to 2×10^{-4} cm/sec
- Hydraulic Gradient 0.012 ft/ft
- Typical Groundwater Seepage Velocity 6 ft/year

Shallow groundwater flow is generally southerly towards a man-made drainage ditch. A single pair of nested wells in the Wisconsin till indicates the presence of an upward gradient within this unit. However, the overall gradient between the Wisconsin and the underlying fractured bedrock is downward (see Section 3.6).

Soil and Groundwater Contamination

An expanded area of affected soil, approximately 250 ft by 165 ft, was delineated during this investigation (see Figure 2.6). BTEX concentrations in soil varied significantly across this zone, with the highest value of 195 mg BTEX/kg soil observed in saturated soils (6 ft below grade) at boring SB-10 near the slop tank. The highest BTEX concentrations were observed within the top 8 ft of soil, with relatively low concentrations (< 0.1 mg/kg) in deeper soils.

The groundwater plume was estimated to be smaller in size than the zone of affected soils, or 140 ft x 90 ft. A total of 14 monitoring wells, mostly screened in the upper 10 ft of the saturated zone or approximately 14 ft below grade, comprised the groundwater monitoring system. Two of these wells measured detectable concentrations of dissolved BTEX components (see Figure 2.7), the highest concentration of Total BTEX being 0.268 mg/L. One deep well, MW-10, was screened from 19-29 ft below grade and exhibited no detectable concentrations of dissolved BTEX compounds.

Natural Attenuation Processes

As described in Section 3.4, vigorous aerobic and anaerobic biodegradation processes were observed at the site. These natural attenuation processes are probably responsible for the presence of clean groundwater in areas with

contaminated saturated soils. In these areas, natural attenuation quickly reduces the concentrations of dissolved BTEX compounds below detectable levels.

In the area south and east of the slop tank, a dissolved phase plume still remains. Several factors may be responsible for the persistence of this plume, including:

- The soils in this area were originally contaminated with larger volumes of JP-4, leading to higher levels of residual phase NAPL that takes longer to dissolve;
- The original extent of the dissolved plume (see Figure 3.1) isolated the current plume area from contact with electron acceptors such as oxygen and sulfate, slowing the dissolution rate from the residual phase NAPL;
- A more recent spill event has recharged the soils in this area with fresh JP-4, but was localized to the current plume area.

The current conceptual model explains the groundwater plume as being in equilibrium with contaminated soils, either soils with a relatively low amount of residual NAPL saturation (~ 5% of pore volume based on TPH data) or soils with adsorbed constituents. Groundwater moves through the 140 ft long plume area very slowly, approximately 6 ft per year seepage velocity, leading to hydraulic residence times of 20+ years.

Based on the monitoring data, the groundwater contains significant biodegradation capacity, defined as the mass of contaminant which can be removed by one liter of groundwater moving from a clean background zone through the plume area (see Appendix C). This parameter, based on the amount of available electron acceptors, was used in a modified BIOPLUME II model to apply the instantaneous reaction assumption for all potential biodegradation pathways, both aerobic and anaerobic. At the Bldg. 735 site, several assumptions were made in determining the total available biodegradation capacity of the groundwater: 1) the background concentrations of oxygen, nitrate, and sulfate were estimated by evaluating data from three clean background wells (GMW-1, GMW-2, and MW-5) and deriving a conservative value for modeling (see table below), 2) the biodegradation capacity resulting from iron reduction and methanogenesis was estimated using the maximum observed concentrations of ferrous iron and methane, and 3) concentrations where oxygen and sulfate utilization slow dramatically were assumed to be 1 mg/L and 10 mg/L, respectively. These values were subtracted from the background concentrations in computing degradation capacity. The calculation of the biodegradation capacity for the Bldg. 735 site is presented below:

Biodegradation Assumption	Units	Dissolved Oxygen	Nitrate	Ferrous Iron	Sulfate	Methane
<i>Electron Acceptor/By-Product Concentration: Range of Results from Monitoring Wells</i>	mg/L	9 - 11.6	0.08 - 44.5	2.8 - < 0.3	46 - 91	0.12 - 1.8
<i>Assumed Uniform Electron Acceptor/By-Product Conc. Used for Modeling</i>	mg/L	10	0.8	1	70	0.95
<i>Assumed Concentration Where Utilization Stops</i>	mg/L	1	0	0	10	0
<i>Utilization Factor</i>	mg/mg	3.14	4.9	21.8	4.6	0.78
<i>Biodegradation Capacity</i>	mg/L	2.8	0.16	0.05	13	1.23

Using oxygen as an example, the biodegradation capacity is calculated as: $(10 - 1) \text{ mg/L} \div 3.14$. Using this approach for all pathways resulted in a total biodegradation capacity at the Bldg. 735 site of about 17.3 mg/L, with most of this capacity coming from sulfate reduction and methanogenesis. The 17.3 mg/L was then converted to an equivalent oxygen concentration in the BIOPLUME II modeling (52 mg/L). This type of analysis was also applied to several other natural attenuation sites evaluated as part of this modeling project (see Appendix C).

3.5.2 Modeling Assumptions

As described in Appendix C, the BIOPLUME II model can be modified to model both aerobic and anaerobic biodegradation using the instantaneous reaction assumption. In this case, the biodegradation capacity was used directly in the model in place of an oxygen-only instantaneous reaction assumption. This approach was used to: 1) predict the maximum extent of plume migration at the Bldg. 735 site, and 2) estimate the time required for the dissolved-phase BTEX plume to completely degrade to non-detect levels.

Several simplifying assumptions were made in this analysis. First, the model was set up to represent a homogeneous, two-dimensional flow field moving to the south-southwest. The assumed hydraulic conductivity of $9.6 \times 10^{-5} \text{ cm/sec}$ was based on the slug test results from the only well located within the plume area.

Second, the entire plume area appears to be in chemical equilibrium with contaminated soils. In other words, the soils in the plume area serve as a source area of dissolved constituents to groundwater due to dissolution from residual

NAPLs and desorption from the organic carbon on the soils. Therefore, the traditional modeling approach, where a solute transport model simulates a limited source area from which a contaminant plume migrates with the moving groundwater, was inappropriate at this site. Rather, the conceptual model for this site indicates that the entire groundwater plume is located in a larger diffuse source area of slightly contaminated soils. Within the plume area itself, moving groundwater brings in available electron acceptors only very slowly, thereby reducing the dissolved phase concentration slowly as well.

The third assumption was that this analysis of plume migration and plume lifetime could be made by modeling all four of the BTEX compounds together. Although these four compounds have different transport and biodegradation properties, it was felt that the sensitivity analysis described below would cover any possible inaccuracies from this approach. The risk assessment calculations, described in Section 4, included separate calculations for each of the four BTEX constituents, and incorporated the physical and chemical properties of each compound.

Fourth, the potential effects of a fluctuating water table were not incorporated into the model. The data used to develop this model were collected in November, with a water table approximately 3-7 ft below grade. Previous technical reports indicate that the water table ranges from 1-5 ft below grade in winter and from 6-9 ft below grade in summer (ESE, 1993). In general, a rising water table is associated with increasing plume concentrations because more contaminated soil is exposed to groundwater and made available for dissolution and desorption. Because the current data were collected during relatively high water table conditions, the input concentrations should represent conservative values.

Note that the uncertainties associated with these assumptions are partially addressed in the sensitivity study, described below, where several key parameters were varied to determine their effects on model predictions.

• **Summary Point: Modeling Assumption**

Major modeling assumptions include: 1) homogeneous conditions exist within the plume area, 2) the site has a shrinking plume that extends over a source area of contaminated soils that are slowly leaching organics to the groundwater, 3) all BTEX constituents can be modeled as a single compound, and 4) fluctuating water tables will not change the current site conceptual model.

3.5.3 Model Set-Up and Calibration

The input parameters to BIOPLUME II used to model the contaminant plume in the Wisconsin till unit are listed in Table 3.1. As described above, a uniform flow field with 6 ft/yr seepage velocity was used in the model to simulate the hydrology of the groundwater system at the site. Detailed site heterogeneities, observed over the entire site, were deemed to be minor components of transport as the plume area is relatively small, and is projected to shrink over time. The finite-difference modeling grid is shown in Figure 3.4.

The BTEX dissolution and desorption process was modeled by increasing the retardation factor in the model to reflect the presence of additional leachable BTEX in the saturated soils. As shown on Table 2.10, there is an estimated 126 grams of dissolved BTEX in the groundwater plume compared to an estimated 5,900 grams of BTEX on the saturated soils in contact with the plume. These mass estimates yield an overall retardation factor of 47, as the retardation factor equals the ratio of dissolved BTEX mass to the total BTEX mass (dissolved BTEX + soil BTEX). Therefore a retardation factor of 47 was used as input to the BIOPLUME II model.

Note that this modeling approach does not match the chemical processes in the plume exactly, as the model simulates release of dissolved constituents from contaminated soils using a linear isotherm assumption. This assumption is standard for soils containing adsorbed hydrocarbons only, but is only an approximation for dissolution of organics from residual NAPLs. While not exact, the differences in the two approaches are relatively minor and the overall extent of NAPLs in the plume area is small enough to make this approach valid for the Bldg. 735 site.

The modeling approach described above resulted in an initial condition in the model where there was much more BTEX in the soil than dissolved in the groundwater, a conclusion supported by the data (see Table 2.10). The BIOPLUME II model was then used to simulate the slow release of BTEX from the soil to the groundwater where aerobic and anaerobic natural attenuation reactions reduced the dissolved BTEX concentrations.

Several calibration runs were conducted to simulate possible plume movement over time to match 1994 conditions. Because the exact timing and magnitude of the JP-4 spill (or spills) is unknown, it is impossible to duplicate the plume movement with any confidence to match the 1994 data. The calibration runs did show that BTEX plumes generated from various release scenarios would begin to

shrink relatively soon after the release, and that the slow groundwater movement at this site restricts the overall movement of the simulated plumes.

3.5.4 Projected Plume Migration and Lifetime

Using BIOPLUME II, a shrinking BTEX plume was simulated from 1994 until it completely dissipated after 15 years (see Figure 3.5). As would be expected, the center of mass of the plume moved downgradient slightly (approximately 40-50 ft), but the edge of the plume never extended beyond the current plume boundary. The simulation indicates that it is unlikely that the organic constituents in the current plume area will ever reach the nearest discharge point, the drainage ditch, located south of the site.

Note that this projection only holds for the dissolved BTEX plume, and not for the contaminated unsaturated and saturated soils on site. The biodegradation processes associated with natural attenuation only degrade dissolved constituents and do not directly attack organics that are adsorbed to the aquifer matrix or present as NAPLs. While lower dissolved-phase concentrations will accelerate the dissolution and desorption of contaminants from soils, these processes are slower than natural attenuation in groundwater and will cause the contaminated soils to persist longer than the contaminated groundwater plume. This can be seen in areas at the site where contaminated saturated soils are observed without seeing contaminants in the groundwater.

3.5.5 Plume Migration and Lifetime: Sensitivity Analysis

A sensitivity analysis of the BIOPLUME model was performed by adjusting several key parameters exhibiting the most uncertainty, and determining the effect on model outcome. Key parameters which were varied include:

- Hydraulic conductivity (estimated value: 9.6×10^{-5} cm/sec)
- Retardation factor (estimated value: 47)
- Available biodegradation capacity (estimated value: 17.3 mg/L)
- Starting concentration (estimated range: 0 - 0.5 mg/L)

To conduct the sensitivity analysis, one of the parameters of interest was increased by 50% and the model was run, followed by a second model run with the same parameter reduced by 50%. The same procedure was followed for the other three parameters, by varying only one parameter during each simulation. The model results were used to generate the maximum plume length and the time required for complete plume degradation for each case in the sensitivity study.

The results of this analysis, shown on Table 3.2, indicate that the most sensitive parameter is hydraulic conductivity. A reduction in the hydraulic conductivity (directly related to seepage velocity) by 50% results in an increase in plume lifetime from 15 years to 29 years. Conversely, an increase in hydraulic conductivity reduces the projected cleanup time to only 10 years. These results are consistent with the fundamental assumptions about this site: the clean groundwater has a very high biodegradation potential (17.3 mg/L), while the observed groundwater concentrations are less than 0.5 mg/L. Although the soil contains much more contaminant than the water, one pore volume of clean groundwater is still enough to remove BTEX to the extent that the dissolved plume disappears. Changing the assumed hydraulic conductivity directly affects the flushing rate of clean groundwater through the contaminated zone.

• **Summary Point: Projected Plume Migration and Lifetime**

Application of a modified BIOPLUME II natural attenuation model indicates that the existing groundwater plume will continue to shrink under the effects of natural attenuation processes. While the biodegradation capacity of the clean groundwater is high, the slow groundwater seepage velocity means that between 10 and 30 years may be required for complete dissipation of the groundwater plume (see Figure 3.5).

3.6 Evaluation of Vertical Migration

A planning-level analysis of vertical migration was conducted to determine the potential for contaminated groundwater to migrate from the shallow Wisconsin till unit underlying the site to the fractured limestone bedrock aquifer that serves as a water supply for the base. The analysis was performed by 1) reviewing existing water well and hydrogeologic data from Grissom AFB, 2) employing MODFLOW, a three-dimensional hydrologic flow model, to simulate vertical groundwater flow conditions at the site, and 3) applying BIOPLUME II, a two-dimensional contaminant fate and transport model, to estimate potential contaminant concentrations at two water supply wells located in the southeast part of the base. Model input data are listed in Table 3.3. A description of the background data and the engineering analysis of vertical migration is provided below.

3.6.1 Geologic and Water Well Background Data

Two main hydrogeologic units are associated with the studied area: the Wisconsin till, unconsolidated glacial deposits composed of clay, silt, sand,

and gravel, extending to a depth of approximately 60 ft below grade; and fractured bedrock consisting of limestone, dolomite, and shale, extending from a depth of approximately 60 ft to 200 ft. A nested pair of wells in the Wisconsin till unit, MW-6 and MW-10, indicates higher hydraulic conductivity in the lower portion of this unit (2×10^{-4} cm/sec measured in the interval 19-29 ft below grade) than in the upper portion (5×10^{-5} cm/sec). The hydraulic conductivity of the fractured bedrock was estimated to be 1×10^{-2} cm/sec based on historical pumping rates and literature information.

A total of eight wells provide water to Grissom AFB and the immediate housing area. The closest drinking water well, #8 located approximately 3000 ft from the Bldg. 735 site, is used as a water supply for the control tower. Wells 6 and 7 are high volume municipal wells used for the main base and base housing, with the closest, well # 7, being located 4500 ft away from the site. All of these wells draw from the fractured limestone bedrock unit and are screened between 125 ft and 180 ft below the surface. The remaining water supply wells are used occasionally for: 1) drinking water when extra capacity is needed, 2) drinking water at remote sites, or 3) water for irrigation, pumped infrequently at low flowrates.

3.6.2 MODFLOW Hydrologic Flow Model Analysis

A three-dimensional hydrologic flow model (MODFLOW) was used to evaluate vertical flowrates from the Wisconsin till unit to the deeper fractured bedrock unit. A 24-by-24 cell finite-difference grid system was developed to include the Grissom AFB area and nearby extraction water wells. For modeling purposes, three units were used to simulate the transmissive zone in MODFLOW: the upper Wisconsin till, lower Wisconsin till, and the fractured bedrock.

The model was calibrated against measured static water level information to define the vertical hydraulic conductivity between the Wisconsin till and the fractured bedrock. Note that static water level data from slightly different time periods were used: data for the silty clay/clayey silt unit were collected in November 1994 as part of this study, while the data for the fractured bedrock were provided by the base personnel in January 1995. These data were considered adequate to continue with this planning-level study. The data indicated relatively low gradients in the upper Wisconsin till (slightly upward in the nested pair of wells) and a larger gradient between the lower Wisconsin till and the bedrock (a 8 ft difference in head across an estimated vertical distance of 106 ft was estimated).

To match these observed data, the vertical anisotropy factor in the MODFLOW model had to be set at 100 (i.e., the ratio of horizontal to vertical hydraulic

conductivity equaled 100) to prevent rapid draining of the silty clay, even with 2.7 inches of recharge per year. While 100 is a relatively high value for this factor, it is not unreasonable considering the potential layering and fine-grained nature of the Wisconsin till. More detailed static water level and hydraulic conductivity data would be required to increase the resolution of this modeling program.

With the calibrated model, hand calculations of the downward flowrate from Wisconsin till to the bedrock over the plume area were performed. These calculations resulted in an estimated value of approximately 30 gallons per day discharge from the plume area in the Wisconsin till to the bedrock below.

3.6.3 BIOPLUME II Model of Fractured Bedrock

A simple BIOPLUME II model of the fractured bedrock was developed with available hydrogeologic data and the results from the MODFLOW analysis. An average plume concentration of 0.2 mg/L was used with the 30 gallons per day flowrate to yield a worst-case mass flux rate into the fractured bedrock. It is important to note that this is an extremely conservative approach, as the existing data indicate that the plume is still concentrated in the upper 10 ft of the saturated zone after many years of potential transport time, and because the deeper soil samples in the Wisconsin till are relatively unaffected. The model was run, therefore, to evaluate a worst-case scenario.

The BIOPLUME II modeling results indicate that no measurable concentrations of BTEX will reach any of the drinking water wells, even after 100 years of operation (steady state condition) and a relatively low amount of assumed biodegradation. To evaluate the sensitivity of the model to biodegradation or other attenuation parameters, the model was run without biodegradation or adsorption for the case of potential transport to the closest main base drinking water wells (#7). Even without adsorption or biodegradation, the model still predicted no measurable concentrations of BTEX in this well, indicating that it is highly unlikely that the Bldg. 735 site will affect the base drinking water wells.

• **Summary Point: Vertical Migration**

Two groundwater models were used to evaluate the potential for downward migration of BTEX constituents from the Bldg. 735 site to the fractured bedrock followed by lateral transport to the water supply wells on the base (see Figure 3.6). The modeling results show no measurable concentrations of BTEX arriving at any of the base water supply wells.

TABLE 3.1
 SUMMARY OF DESIGN PARAMETERS USED IN BIOPLUME II
 MODEL FOR SILTY CLAY/CLAYEY SILT UNIT

Treatability Study/Focused Feasibility Study
 Building 735 Site, Grissom AFB, Indiana

Parameter	Model Input Value	Basis for Selection
a) Soil Classification	Silty Clay/ Clayey Silt	<ul style="list-style-type: none"> Typical soil type of uppermost aquifer unit determined from available geologic logs (see Appendix C).
b) Saturated Thickness (ft)	10	<ul style="list-style-type: none"> Typical value for silty clay/clayey silt unit determined from available geologic logs (see Appendix C).
c) Effective Porosity (unitless)	0.20	<ul style="list-style-type: none"> Typical value for soil type determined from literature.
d) Hydraulic Conductivity (cm/sec)		<ul style="list-style-type: none"> Characterized on basis of results of on-site aquifer rising-head and falling head slug tests (see Table 2.2).
• Mean:	5.55×10^{-5}	
• Plume Area Value:	9.61×10^{-5}	
e) Transmissivity (ft ² /day)	2.72	<ul style="list-style-type: none"> Calculated from average saturated thickness and hydraulic conductivity values shown above.
f) Lateral Hydraulic Gradient (ft/ft)	0.012	<ul style="list-style-type: none"> Typical value determined from static water level surveys (see Figure 2.5).
g) Lateral Seepage Velocity (ft/yr)	6.0	<ul style="list-style-type: none"> Calculated from hydraulic parameters listed above for affected plume area.
h) Longitudinal dispersivity (ft)	10	<ul style="list-style-type: none"> Based on scale factor of 0.1 of the plume length.
i) Transverse dispersivity (ft)	3.3	<ul style="list-style-type: none"> 33 % of longitudinal dispersivity.
j) Anisotropic ratio (unitless)	1	<ul style="list-style-type: none"> Value based on assumed isotropic conditions.
k) Organic fraction of soil (% weight)	0.245%	<ul style="list-style-type: none"> Mean value based on laboratory analyses of soil samples from well MW-9 and soil boring SB-3 (see Table 2.4).
l) Modified retardation factor (unitless)	47	<ul style="list-style-type: none"> Determined based on bulk density of soil in silty clay unit, effective soil porosity, and modified distribution coefficient accounting for both NAPL and adsorbed hydrocarbon on soil as observed in soil samples.
m) Detected BTEX concentration (mg/L)	0.187-0.268	Recent groundwater sampling event (see Table 2.6).
n) Available electron acceptor as equivalent oxygen concentration for Bioplume II (mg/L)	52	Based on field measurement of background electron acceptors and mass ratio of oxygen, nitrate, sulfate and methane to benzene. Values have been converted to oxygen equivalent for modeling purposes (see Figure 3.3).
o) Affected Groundwater Plume Area (ft ²)	9740 (140 ft x 70 ft)	<ul style="list-style-type: none"> Plume area and concentrations based on BTEX concentration detected in recent groundwater sampling event (see Table 2.6 and Figure 2.7).

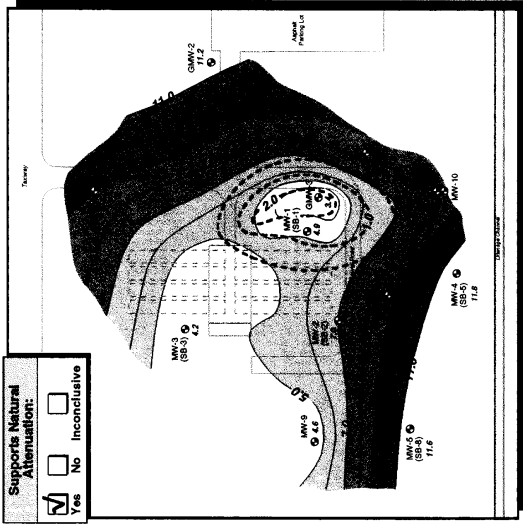
TABLE 3.2
BIOPLUME II MODEL SENSITIVITY ANALYSIS:
COMPARISON OF RATE OF NATURAL ATTENUATION USING
UNCERTAINTY FACTOR OF $\pm 50\%$ FOR KEY PARAMETERS

Treatability Study/ Focused Feasibility Study
 Building 735 Site, Grissom AFB, Indiana

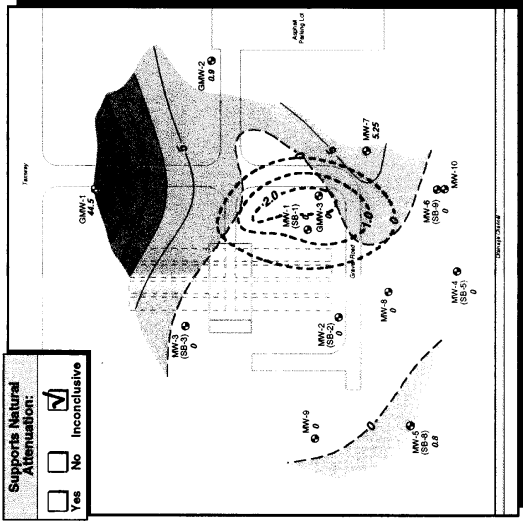
CASE	Predicted Plume Length After 5 Years (ft)	Time Required for Complete Degradation (Yrs)
<i>Base Case</i>	100	15
<i>Hydraulic Conductivity</i>		
+50%	90	10
-50%	130	29
<i>Retardation Factor</i>		
+50%	100	15
-50%	100	15
<i>Biodegradation Capacity</i>		
+50%	90	13
-50%	110	17
<i>Initial BTEX Concentration</i>		
+50%	110	16
-50%	90	13

Note:

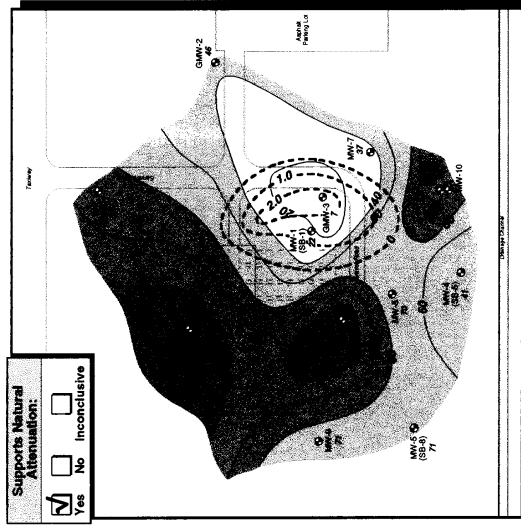
1. Base case input parameters used in Bioplume II model see Table 3.1.
2. Base case hydraulic conductivity: $K = 9.61E-05$ cm/sec.
3. Retardation factor increased in model to account for residual hydrocarbons in saturated soils in plume area. Base case Retardation factor: $R = 47$.
4. Base case biodegradation capacity: 17.3 mg/L (52 mg/L Bioplume II Oxygen equivalents).
5. Base case initial BTEX concentrations = 0.1 - 1.0 mg/L.



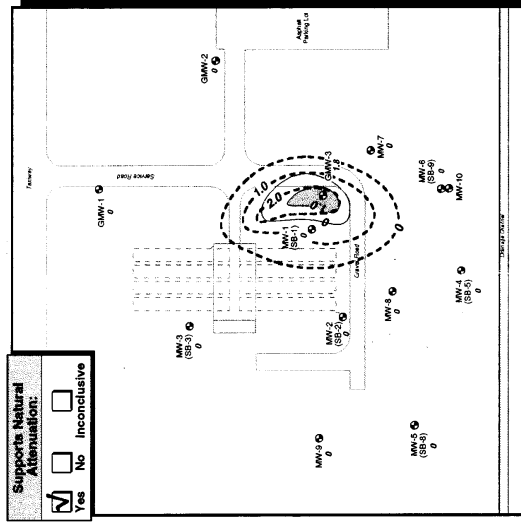
Dissolved Oxygen in Groundwater (mg/L)



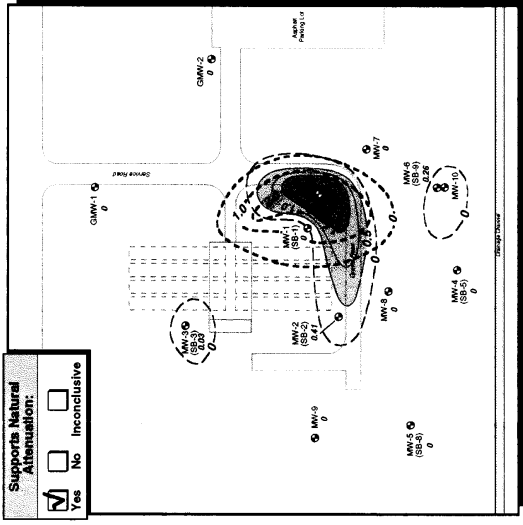
Nitrate in Groundwater (mg/L)



Sulfate in Groundwater (mg/L)



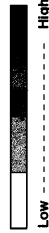
Methane in Groundwater (mg/L)



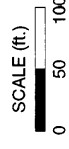
Dissolved Ferrous Iron in Groundwater (mg/L)

LEGEND

- Monitoring well location
- Concentration contours of constituent in groundwater. Variable contour interval.
- Concentration of indicated constituent in groundwater
- BTEX concentration contour (mg/L)



NOTES: 1) Laboratory analysis results can be found on Tables 2.7 - 2.8.
2) Blowing/stripping system in operation within plume area during specific analyses.
3) All values represent less than detection limit for specific analyses.

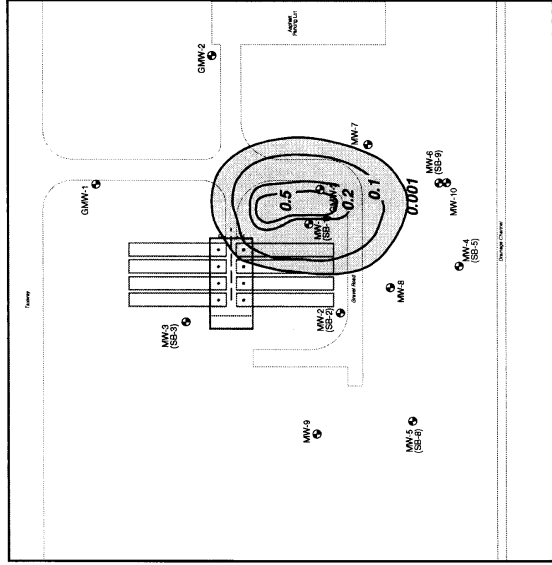


Groundwater Services, Inc.
Houston, Texas

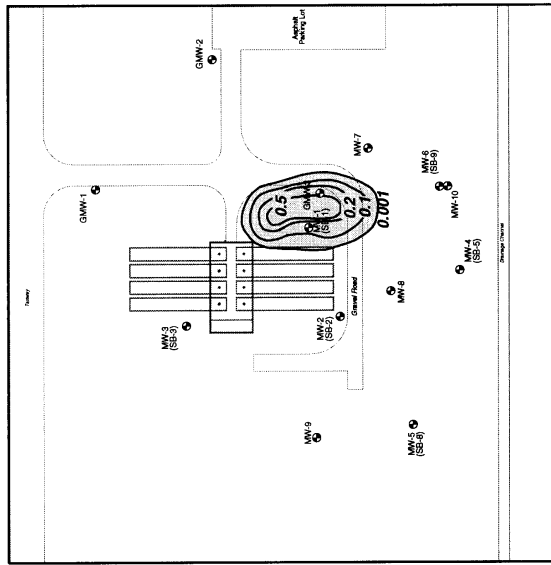
DISTRIBUTION OF ELECTRON ACCEPTORS AND METABOLIC BY-PRODUCTS FROM NATURAL ATTENUATION: November 1994
Treatability Study/Focused Feasibility Study
Building 735 Site, Grissom AFB, Indiana

GSJ Job No:	G-1584	Drawn By:	DLB
Revised:	3/31/95	Checked By:	JAS
Reviewed:	6/2/95	Approved By:	CJN
Scale:	As Shown		

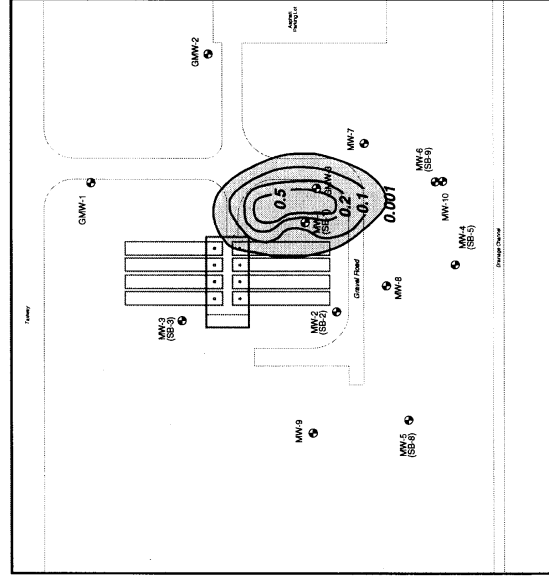
FIGURE 3.3



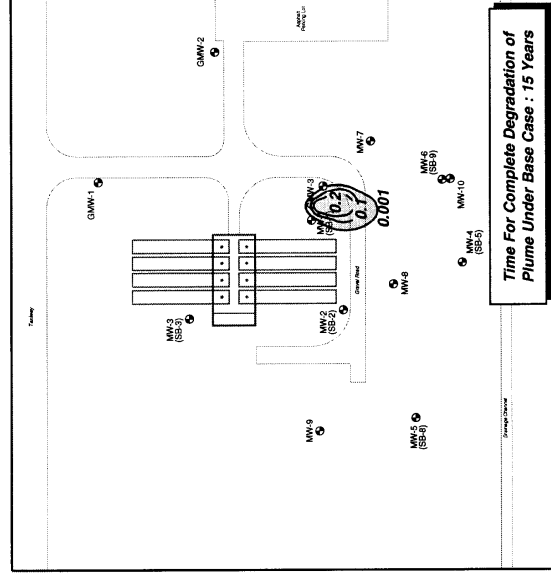
Simulated Current Total BTEX Concentrations (mg/L)



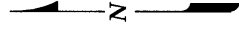
Simulated Total BTEX Concentrations After 5 Years (mg/L)



Simulated Total BTEX Concentrations After 2 Years (mg/L)



Simulated Total BTEX Concentrations After 10 Years (mg/L)



LEGEND

Monitoring well location.

— 0.1 — Contours of Total BTEX Concentrations (mg/L)

NOTE:

- 1) Simulation of BTEX plume in Wisconsin till unit.
- 2) BTEX - Benzene, toluene, ethylbenzene, xylenes.
- 3) See Table 3.1 for design basis information used in Bioplume II Model.
- 4) Assumed reactions: oxygen reduction, nitrate reduction, sulfate reduction, and methane genesis. Total equivalent oxygen concentration = 52 mg/L.

SCALE (ft.)
0 50 100



**Groundwater
Services, Inc.**
Houston, Texas

SIMULATED BASE CASE TOTAL BTEX CONCENTRATION OVER TIME FROM BIOPLUME II MODEL

Treatability Study/Focused Feasibility Study
Building 735 Site, Grissom AFB, Indiana

GSI Job No:	G-1584	Drawn By:	XML
Issued:	3/31/95	Chkd By:	CJN
Revised:	6/2/95	App'd By:	CJN
Scale:	As Shown		

FIGURE 3.5

4.0 RISK ASSESSMENT

As detailed in Section 2.0 of this report, investigations conducted at the Building 735 site have confirmed the presence of organic constituents of concern at concentrations exceeding background levels in shallow soils and groundwater underlying the site. To support the development of a Focused Feasibility Study for managing these constituents, available site information was used to:

- Conduct a baseline exposure assessment to evaluate source zones, active pathways, and potential receptors;
- Perform baseline risk calculations associated with active pathways;
- Calculate applicable media cleanup levels for affected media.

The following sections detail the methodology and results from each of the tasks.

4.1 Baseline Exposure Assessment

4.1.1 Primary and Secondary Source Zones

Remedial investigations conducted to date have shown historical releases of JP-4 to be the primary cause of affected soil and groundwater detected at the site. The two primary release mechanisms included infiltration of fuel into the subsurface and possible surface discharges (see Figure 4.1). The secondary sources associated with the known area of waste release are as follows:

- 1) ***Affected Surface Soils:*** BTEX-containing soils have been detected at the site from 1 to 30 ft. Because different risk calculations are performed for different soil intervals, *surface soils* are defined as extending between 0-2 ft below grade and *subsurface soils* are defined as extending between 2 ft and the water table. At the Bldg. 735 site, contaminated *surface soils* are found in most, but not all, of the soil borings (see Figure 2.7).
- 2) ***Affected Subsurface Soils:*** Soil samples collected between 2 ft below grade and the observed water table indicate the presence of affected *subsurface soils* at the site. During the sampling performed for this project, the water table was found 3-7 ft below grade, and is reported to range between 1-9 ft below grade depending on the season.
- 3) ***Non-Aqueous Phase Liquids*** Residual non-aqueous phase liquids (NAPLs) were detected at one soil boring using a field test method, and are indicated as potentially being present in other soil samples based on

observed concentrations of organics. No mobile free-phase has been detected in any of the monitoring wells during the 1994 sampling program, although 50 gallons of free-product was removed in 1991.

- 4) *Affected Groundwater Plume:* Dissolved concentrations of various waste constituents have been detected in groundwater samples from monitoring wells located in a 140 ft by 90 ft area located generally south of the slop tank (see Figure 2.8).

4.1.2 Air Exposure Pathway

The presence of affected surface soils constitutes an active air exposure pathway to on-site and off-site receptors via surface volatilization and/or particulate transport. Volatilization from subsurface soils also represented an active air pathway via volatilization (see Figures 4.1 and 4.2-1 and 4.2-2). Standard exposure factors for vapor inhalation and dust ingestion are shown on Table 4.1, and site specific data are shown in Table 4.2.

4.1.3 Groundwater Exposure Pathway

For this exposure assessment, human exposure via ingestion or dermal contact with affected groundwater at a hypothetical water supply well was addressed. As illustrated on Figures 4.1, 4.2-3, and 4.2-4, mechanisms for constituent release and transport within the shallow groundwater flow system include: i) downward leachate percolation from affected soils and ii) lateral migration of affected groundwater within the water-bearing till unit. Because the plume has had enough time to reach equilibrium with the soils, the risks associated with leaching soils was assumed to be represented by the actual groundwater migration pathway.

Since the current land use in the immediate vicinity of the Bldg. 735 site is industrial with tightly controlled-access, residential exposure factors were not appropriate for the plume area itself. Groundwater migration in the till unit to potential off-site wells located 3500 ft to the southwest was evaluated.

As discussed in Section 3.5, migration of site constituents to the fractured bedrock aquifer is not evident in the data from this study. If this vertical migration was active, however, modeling indicates that natural attenuation processes would reduce the concentrations of these constituents to zero or non-detectable values at the drinking water wells (see Section 3.6). Therefore, the fractured bedrock groundwater pathway was assumed to be incomplete.

Standard exposure factors for groundwater ingestion and dermal contact for offsite residential exposure are listed on Table 4.1. Site specific data are presented in Table 4.2.

4.1.4 Surface Soil/Sediment Exposure Pathway

In areas where affected soils, sediments, or waste materials are present in the top 2 ft of soil, human exposure can occur via direct contact (see Figure 4.2-5). Because the Bldg. 735 site is under controlled access from residential receptors, the only active potential receptors associated with this pathway were construction workers. Two general cases were evaluated:

- Case 1: A health and safety plan for soils contaminated with BTEX is in place, therefore protecting construction workers from exposure by requiring air monitoring and use of appropriate personal protective equipment (PPE).
- Case 2: Standard construction practices are in place, therefore requiring soil remediation to safe levels in order to prevent potential exposure of construction workers to inhalation of vapors, dust ingestion, and dermal contact.

Standard exposure factors for the surface soil pathway are provided on Table 4.1, with site specific data shown in Table 4.2.

4.1.5 Surface Water Exposure Pathway

Surface discharge of affected groundwater represents the only current potential pathway for release of hazardous constituents to local surface water (see Figure 4.1 and 4.2.6 and 4.2.7). As discussed in Section 2.0 of this report, groundwater flow in the Wisconsin till discharges into the drainage ditch at the site. Although the site is under controlled access, the ditch flows to the west where there may be the potential for recreational contact with on-site personnel. Standard exposure factors and site specific data for this pathway are provided on Table 4.1 and 4.2, respectively.

The surface water runoff pathway (runoff collecting contaminants from surface soils) was considered to be inactive because: 1) the contaminated surface soils data from this study were collected from 1.5-2 ft below grade, depths which would not contribute to the generation of runoff contamination, 2) the potential for continued leaching of volatile constituents to runoff for several years after a

release is low, and 3) previous investigations did not identify surface water runoff as an active pathway.

4.2 Baseline Risk Calculations

4.2.1 Chemical Characteristics of Affected Media

Selection of Constituents of Concern

As discussed in Section 2.0 of this report, soils and groundwater underlying the Bldg. 735 site have been found to contain BTEX constituents at concentrations exceeding background levels.

Toxicological Information

Detailed information on the chemical, physical, and toxicological properties of all hazardous constituents confirmed to be present at the Bldg. 735 site, as required for calculation of risk-based media cleanup levels, is provided in Appendix E of this report. Summary data regarding relevant toxicological parameters is provided on Table 4.3.

For the purpose of this baseline risk assessment, information regarding human health risks associated with each constituent of concern has been obtained from the *EPA Integrated Risk Information System (IRIS)* or the *EPA Health Effects Assessment Summary Tables (HEAST)*. On Table 4.3, known or suspected carcinogenic compounds have been classified in accordance with EPA Guidelines for Carcinogenic Risk with data obtained from IRIS. When available, the published cancer slope factors are indicated. For compounds not known or suspected to be carcinogens, published Reference Dose values for ingestion and inhalation are provided. For substances with both published slope factors and reference doses, media cleanup levels have been determined based on carcinogenic effects. Hazard quotients for known carcinogens have also been included in calculating total hazard index values for the various exposure pathways.

4.2.2 Baseline Health Risks for Exposure Pathways

This section describes the results of the risk calculations for each identified exposure pathway under the two cases considered for the site (i.e., Case 1 involving all pathways except for construction worker exposure and Case 2 in which all pathways are considered including construction workers). General risk goals for this site included maintaining individual compound carcinogenic risk

below 1×10^{-6} (i.e., no more than 1 additional cancer case in an exposed population of 1,000,000) and cumulative target hazard index goal for systemic toxicants of 1.0, which assumes that all individual constituents affect the same organ/system. As discussed in Section 4.3, the cumulative excess lifetime carcinogenic risks and total hazard index are calculated using a set of conservative assumptions which probably overestimate the risk associated with a site.

As described below, target risk goals were exceeded for only one potential receptor: construction workers working in contaminated soils (Case 2; see Table 4.4).

Air Exposure Pathway

Under current site conditions, human exposure to site constituents via inhalation of volatilized vapors or ingestion of airborne particulates was not found to be a critical pathway for either on-site or off-site receptors. Based upon available soil test results at the site, ambient vapor levels immediately above the affected surface and subgrade soil zones are not expected to exceed OSHA Permissible Exposure Limits (PELs), thereby presenting no threat to base personnel working on-site (see Pathways 1A and 2A on Figure 4.2; results are presented in Table 4.4). Note that this pathway is extremely conservative, as the point of exposure assumed that base personnel are breathing air immediately over the site for 250 days per year over a 25 year period.

For off-site residential receptors (Pathways 1-B and 2-B), excess lifetime carcinogenic risks are predicted to be 4.4×10^{-7} (less than the target goal of 1.0×10^{-6}) and the total hazard index is predicted to be 2.1×10^{-2} (less than the target goal of 1.0) as shown in Table 4.4. Again this pathway was based on an extremely conservative assumption of a hypothetical residential receptor located immediately across the closest property boundary, a distance of 2500 ft from the site. The closest actual residential receptors are actually personnel living in on-site base housing 3250 ft away.

Groundwater Exposure Pathway

The initial exposure assessment identified groundwater migration and ingestion from off-site Wisconsin till drinking water wells as a possible exposure pathway (Pathway 4 on Figure 4.2). On the basis of the groundwater modeling described in Section 3.5, however, no risks were associated with ingestion of groundwater by an off-site hypothetical receptor well because groundwater modeling indicates that the plume is shrinking due to the effects of natural

attenuation. These findings are confirmed by the field investigation which indicate that the groundwater contaminant plume is shrinking (see Section 3.4). Therefore, the shallow groundwater pathway appears to be incomplete (see Table 4.4).

As described in Section 3.6, the vertical flow/fractured bedrock model indicated that vertical migration of site constituents to the fractured bedrock aquifer and subsequent transport to drinking water wells would result in no detectable concentration of these constituents in the wells. In addition, the non-detected groundwater test results from monitoring well MW-10, screened within the deeper Wisconsin interval, suggest that no downward migration of constituents has taken place. Based on this information, this deeper groundwater pathway was also considered to be incomplete (see Section 4.1.3).

Soil Exposure Pathway

The soil exposure pathway was active only for Case 2, under the assumption that future construction workers will be exposed to contaminated surface and subsurface soils. Under this scenario, the risks associated with dermal contact (Pathway 5), and vapor inhalation and dust ingestion (Pathways 1 and 2) yielded a carcinogenic risk value of 1.2×10^{-6} , slightly greater than the 1×10^{-6} guideline. However, if an appropriate health and safety plan is implemented as described in Case 1, the risks to construction workers from these soils is managed and the risk goal is not exceeded.

Surface Water Exposure Pathway

As with the groundwater pathway, modeling and field data results indicate that the groundwater plume is shrinking, therefore posing no risk to surface water receptors (Pathway 7). Although the groundwater from the Wisconsin till unit in the plume area will eventually discharge into the drainage ditch (over a period of 20-50 years), natural attenuation is projected to remove all of the BTEX constituents before the plume reaches the drainage ditch. Note that even in the case of a moving plume, this pathway would not pose any risk to surface water receptors as the Indiana water quality criteria specifies benzene concentration must be below 0.4 mg/L, which is higher than the maximum observed plume concentration (0.25 mg/L). Benzene has the most stringent water quality criteria of any of the compounds detected.

4.3 Evaluation of Uncertainty in Baseline Risk Estimates

Uncertainty in the estimation of baseline risk levels is introduced by assumptions regarding site-specific conditions, relevant exposure factors, and toxicological parameters. In order to provide a conservative estimate of potential human health effects, parameters employed in this baseline risk assessment have been selected so to contribute to an over-estimation of the actual carcinogenic risk and hazard index levels associated with the site. A qualitative review of critical uncertainty factors and their effect on the baseline risk estimate is provided below.

4.3.1 Site-Specific Uncertainty Factors

For the purpose of the baseline risk assessment, source zone concentrations and potential human exposure mechanisms have been characterized on the basis of available site information. Key assumptions regarding the physical setting of the site include: i) the type and concentrations of constituents present in affected soil and groundwater, ii) current and anticipated institutional controls, and iii) relevant exposure pathways. On the basis of these data, transport models have been used to predict the maximum chronic exposure levels likely to occur at potential points of exposure. The effect of site data, modeling, and exposure assumptions on the results of the baseline risk assessment are addressed below.

<i>PARAMETER</i>	<i>EFFECT</i>
Source Zone Characterization: As a conservative measure, constituent concentrations throughout the full source zone area have been assumed to be equal to the upper-range concentrations (i.e., maximum value or upper 95% confidence limit of mean) measured in site samples. Use of such upper-range source zone concentrations and dimensions has likely contributed to a significant overestimation of associated health risks.	<i>Overestimation of Risk</i>
Relevant Exposure Pathways: Chronic human exposure to site constituents via air, surface water, or groundwater transport mechanisms has been assumed to occur from contact either i) directly at the source zone or ii) at the nearest potential off-site residence downgradient of the source. At the present time, measurable concentrations of site constituents have not been detected at the hypothetical off-site points of exposure assumed for the purpose of this study. Since the source is known to have been present at the site for more than 15 years (see Section 2.1.1), it does not appear likely that site constituents will migrate to hypothetical off-site receptor points.	<i>Overestimation of Risk</i>

PARAMETER**EFFECT**

Model Type and Applicability: Air and groundwater transport mechanisms have been characterized on the basis of two-dimensional transport models shown to provide a reasonable, conservative estimate of steady-state migration patterns in prior applications. These standard procedures are not anticipated to contribute to either a significant over- or underestimation of site risk.

Unknown

Effect of Fluctuating Water Table: A lower water table would yield higher URC (upper range concentrations) for benzene in subsurface soils because one saturated soil sample had a higher benzene concentration (24 mg/kg) than the assumed URC for the unsaturated soils (11 mg/kg). If these soils were permanently dewatered, then the associated risk would increase in selected air and soil pathways. If the soils are exposed only part of the time, then the risk from these soils is reduced proportionately. Because of the complexity in addressing the fluctuating water table, typical conditions assuming a water table 3-7 ft below grade was assumed.

*Possible
Underestimation
of Risk*

4.3.2 Exposure Factor Uncertainty

For the purpose of this baseline risk assessment, exposure factors used to characterize potential chemical intake rates at points of exposure have been based upon standard values for contact rates, exposure frequency and duration, and human body weight, as specified under applicable EPA guidelines. The effect of these standard exposure factors on the risk levels calculated for a typical corrective action site is addressed below.

PARAMETER**EFFECT**

Contact Rates: Many of the standard contact rates specified under EPA guidelines are at or near the upper-range limits for human consumption (e.g., two liters/day water, 20 cu.m./day air intake), as determined from EPA surveys (see EPA Superfund Risk Assessment Guidance). Consequently, use of these values introduces a significant degree of conservatism into the risk calculations.

*Overestimation
of Risk*

Constituent Intake and Absorption: Receptors have been assumed to absorb the full constituent mass contained within the consumed media (e.g., air, water, soil), with no allowance for constituent breakdown, pass-through, or exhalation. For most constituents, this assumption is likely to overestimate potential health effects associated with human exposure.

*Overestimation
of Risk*

4.3.3 Toxicological Parameter Uncertainty

Toxicological parameters used in this risk assessment have been based upon published values obtained from the *EPA Integrated Risk Information System (IRIS)* or the other supplementary sources. A summary of toxicological values used for each critical constituent and relevant data sources is provided in Table 4.3 and Appendix E. The effect of these parameters on the results of the baseline risk assessment is addressed below.

<i>PARAMETER</i>	<i>EFFECT</i>
Toxic Reference Dose Values: For constituents identified as systemic toxicants, the EPA has derived reference dose values by applying safety factors of 10 - 10,000 to threshold response levels determined in clinical or laboratory studies. Safety factors are adjusted in accordance with the general quality of the human dose-response data for each constituent and, consequently, introduce a variable degree of conservatism for sites containing multiple constituents. Based on available information, the effect of these parameters on the results of the baseline risk assessment is not clearly defined.	<i>Unknown</i>
Carcinogenic Slope Factors: Slope factors for carcinogenic effects represent the upper 95% confidence limit for a low-concentration dose-response curve, extrapolated from high-concentration dose-response data using the linearized multi-stage (LMS) model. In general, the LMS model is considered to provide an upper-range estimate for human health effects associated with chronic exposure to low-level constituent concentrations. As a further conservative measure, suspected carcinogens (i.e., Class C) are considered equivalent to known or probable carcinogens (i.e., Class A or B, respectively) in terms of the ability to trigger cancer upon trace exposure to sensitive populations. Therefore, use of published slope factors to calculate carcinogenic risk will generally contribute to a conservative overestimate of potential health effects.	<i>Overestimation of Risk</i>
Synergistic Effects: Research has indicated that exposure to certain combinations of constituents can result in a higher incidence of carcinogenic effects than would be caused by exposure to the individual constituents at equivalent levels. At present, insufficient data regarding such synergistic effects is available to support quantitative analysis as part of a baseline risk assessment. However, failure to account for such effects, if present, could contribute to underestimation of risk levels.	<i>Under-Estimation of Risk</i>

4.3.4 Summary of Risk Calculation Uncertainty

Based on the above analysis, risk levels appear to be calculated in a conservative manner (i.e., risk levels have been overestimated on the whole). A large number of the above uncertainties have been accounted for by taking the "worst-case" assumptions. Only two factors, the fluctuating water table and synergistic effects, can be said to possibly contribute to underestimation of risk. At present, research data are not sufficient to predict whether synergistic effects would result from the mixture of chemicals present at the site. The fluctuating water table could increase the overall risk to some degree.

4.4 Applicable Media Cleanup Levels

Based upon available information regarding affected environmental media and relevant exposure pathways, soil and groundwater cleanup levels have been estimated for the Bldg. 735 site. In each case, the concentration required to achieve either the risk goals or hazard quotient goals was defined as the appropriate media cleanup standard for each media (see Table 4.5). For example, the construction worker receptor was estimated to be exposed to a 1.2×10^{-6} carcinogenic risk factor under Case 2, where standard construction procedures were assumed. To achieve the risk goal of 1×10^{-6} , a 17% reduction in benzene concentration was required. Under Case 1 however, no reduction would be required because the implementation of a health and safety plan for construction workers would manage these risks.

As shown in Table 4.5, groundwater cleanup standards are all defined as being higher than the solubility limit of the constituent in water ($>S$). The greater-than-solubility results from modeling projections of no plume migration to drinking water wells (hypothetical or actual) or to surface water discharge due to the effects of natural attenuation.

The cleanup standards for Case 1 and Case 2 were used to develop the remedial action objectives in the Focused Feasibility Study discussed in Section 5.

5.0 FOCUSED FEASIBILITY STUDY

5.1 Objectives

To address affected soil and groundwater at the Building 735 site, a Focused Feasibility Study (FFS) has been conducted by: 1) defining remedial action objectives and general response actions, 2) screening technology process options, 3) assembling technologies into remedial alternatives, 4) performing a detailed analysis of the alternatives, and 4) comparing the alternatives against nine evaluation criteria (e.g., effectiveness, implementability, cost, etc.). Application of the FFS methodology at this site was requested by the Indiana Department of Environmental Management (IDEM) in planning meetings and in comments to the project workplan submitted September 28, 1994.

While a standard Feasibility Study considers a wide range of remedial alternatives, Focused Feasibility Studies concentrate on a narrow selection of preferred technology process options, proven to be effective at sites having similar characteristics to the site currently under consideration. At the Bldg. 735 site, natural attenuation has been identified as a potential remediation alternative of interest for addressing affected groundwater. Results from the natural attenuation Treatability Study (see Section 3.0) have been used to develop key design data that can be used in the FFS.

The US EPA *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* was used to develop this FFS. Results of the FFS may be used as part of a Decision Document for the Bldg. 735 site under Indiana Department of Environmental Management UST Guidance (IDEM, 1993). Remedy development and evaluation have been based on current IDEM guidelines regarding site characterization and feasibility studies.

5.2 Conceptual Model

As described in Section 2.0 of this report, the current conceptual model for the site includes two affected media:

- **Affected surface and subgrade soils;** Affected surface and subgrade soils were observed to contain BTEX compounds and elevated levels of TPH. The highest concentration of BTEX measured in soil is 195 mg/kg. The total extent of the affected soil zone is approximately 250 ft long by 165 ft wide. Within the context of this report, all discussion of *soil* risk assessments and remediation deals with those contaminated soils above

the water table, approximately 3-7 ft BGS during this study. Note that the water table appears to fluctuate between 1-3 ft BGS in winter (December-May) and 6-9 ft BGS during summer (June-November).

- **Dissolved groundwater plume;** An affected groundwater plume that measures about 140 ft long by 90 ft wide exists at the Bldg. 735 site. This plume appears to be limited to a depth of ten feet below the water table. A maximum plume concentration of 0.268 mg/L BTEX was measured in well GMW-3. Note that *saturated* soils (those below 3-7 ft BGS) containing BTEX compounds are considered as part of the groundwater media because the exposure pathways and remediation technologies are all groundwater based.

Past remediation efforts at the site have included limited excavation, free product removal, and installation of a combined bioventing/air sparging system that is currently in operation. This 8-well treatment system was originally designed to biovent unsaturated soils over an area extending approximately 50 ft northwest to 100 ft southeast of the slop tank. The wells were screened to 11 ft below grade to allow bioventing of the deeper soils during the summer months when the water table is low. During periods with a high water table, the system behaves as an air sparger wherein water is bubbled through a long drop tube located inside each well, providing oxygen to the groundwater. System performance data indicates a significant reduction in soil BTEX concentrations in areas near the bioventing system. While some increase in the dissolved oxygen concentration of groundwater has been observed, the overall impact of the air sparging system is difficult to assess (see discussion below).

The risk assessment performed for this project (see Section 4) indicates very low risks to potential receptors from the affected media, particularly if moderate institutional controls are implemented at the site. Potential groundwater receptors include persons coming in contact with groundwater as it discharges into the shallow drainage ditch south of the site, and users of any offsite residential drinking water wells screened in the Wisconsin unit. Even with the use of very conservative assumptions, risk levels associated with transport of site constituents in the upper silty clay/clayey silt aquifer were well below the 10^{-6} level and no non-carcinogenic hazards were identified. A companion study of the potential for downward migration of constituents to the fractured bedrock aquifer used as the base water supply (confirmed by sampling results from deep monitoring well MW-10) indicated this pathway was not a threat to human health (see Section 3.6 for discussion of vertical migration).

In performing the risk assessment for affected surface and subsurface soils (soils above the water table) three potential exposure pathways were evaluated: 1) offsite vapor transport and vapor inhalation by residential receptors, 2) vapor inhalation and dust ingestion by on-site base workers, and 3) vapor inhalation, dust ingestion, and dermal contact by remedial activity construction workers exposed to contaminated soils. The risk assessment concluded the only significant risk to be associated with the construction work scenario, which yielded a risk level of 1.2×10^{-6} .

5.3 Technology Screening

5.3.1 Remedial Action Objectives

Based on the results of the risk assessment (see Section 4), three site-specific remedial action objectives have been identified. These objectives are:

1. Prevent offsite migration of affected groundwater.
2. Prevent discharge of affected groundwater to the drainage ditch south of the site.
3. Protect the health and safety of workers who may be exposed to affected soils.

5.3.2 General Response Actions

To satisfy the site-specific remedial action objectives, two general response actions have been developed. The general response actions are each associated with a specific media as follows:

1. *Groundwater*: Control migration of the groundwater plume within the Wisconsin unit.
2. *Soils*: Control exposure to affected surface and subsurface soils.

5.3.3 Technology Screening

A technology screening analysis, based upon the nature of observed site contaminants and site conditions at the Bldg. 735 site, was conducted to evaluate potentially applicable remediation technology process options. Performance and costs for each alternative were characterized on the basis of engineering

judgment, previous experience with these technologies, and available literature. Two primary resources used for this screening were the *Remediation Technologies Screening Matrix* (U.S. EPA *et al.*, 1993) and the *Remediation Technology Comparison Compiled by EPA and the U.S. Air Force* (Hazardous Waste Consultant, 1994) .

As specified in the FS guidance, the potential remedial technology process options are to be evaluated on the basis of three criteria:

- **Effectiveness:** This criteria assesses the ability of a process option to meet the remedial action objectives. Both long-term and short-term effectiveness are evaluated. Short-term effectiveness considers the time required to implement the remedy and any adverse effects on public health or the environment during the construction or implementation period. Long-term effectiveness considers the ability of the technology to achieve and maintain the design objective for the site and includes an assessment of the reduction in contaminant toxicity, mobility, or volume provided by the technology.
- **Implementability:** This criteria assesses the technical and administrative feasibility of construction, reliable operation, and achievement of regulatory, O&M, and monitoring requirements. Factors such as availability of treatment, storage and disposal services; ability to obtain applicable permits; availability of necessary equipment and workers are taken into account.
- **Cost:** This criteria assesses the capital and O&M costs of the technology and identifies those process options that exhibit a cost which is grossly disproportionate compared to the level of effectiveness achieved. Detailed cost estimates are not prepared. Rather, technologies are evaluated based on published unit costs for comparison.

Several alternative process options, ranging in complexity from natural attenuation to intensive source controls, have been identified as generally applicable to the general response actions identified at the Bldg. 735 site. A preliminary screening of these process options with regard to the remedial action objectives and the above EPA screening criteria is presented below and summarized in Table 5.1.

TECHNOLOGY PROCESS OPTION FOR GROUNDWATER

RETAINED/ELIMINATED

Natural Attenuation: This remedy verifies that contaminants are being destroyed by natural biodegradation processes and quantifies the rate of the biodegradation process. The maximum extent and duration of plume migration is estimated to ensure that potential receptors are not exposed to hazardous constituents while the affected media are undergoing natural attenuation. This technology incurs low life-cycle costs since capital costs are minimal. O&M costs are limited to long-term monitoring and reporting requirements. The treatability study of natural attenuation verified the presence of vigorous natural biodegradation processes at the Bldg. 735 site.

Retained

Air Sparging: In the air sparging process, air is injected at high flow rates into the saturated zone. Dissolved organics are removed from the groundwater through volatilization. At lower air flow rates, air sparging provides oxygen to the groundwater to facilitate in-situ bioremediation. This technology is especially effective in homogeneous media where biodegradable volatile organic chemicals are observed. At the Bldg. 735 site, air sparging is probably not an effective stand-alone technology due to the heterogeneous nature of the aquifer that prevents proper distribution of the sparge channels. However, because there is an existing air sparging system combined with the bioventing wells now in operation at the site, and because some effects of the sparging system have been observed in groundwater, the air sparging alternative has been retained for the Bldg. 735 site.

Retained

Aquifer Dewatering/Soil Vapor Extraction: This combined soil/groundwater remedy involves the installation of recovery wells with drop tubes connected to vacuum headers; installation of a skid-mounted vacuum system for combined water and vapor extraction; and treatment of collected groundwater and vapors. Although low aquifer transmissivity may limit the rate of fluid and vapor extraction from the silty clay unit underlying the Bldg. 735 site, this approach is generally more effective in terms of organic mass removal than either groundwater pump-and-treat or in-situ biodegradation systems. This approach incurs high capital costs, but the technology is proven and is easily implementable.

Retained

Groundwater Pumping and Treatment: This remedy includes recovery well installation, on-site treatment of recovered groundwater, and discharge or reinjection of treated groundwater. Groundwater monitoring is employed to gauge the effectiveness of the remedy and to ensure compliance with remedial action objectives. Although this technology is readily implementable at the Bldg. 735 site, aquifer heterogeneity, low transmissivity, and presence of NAPL limit the effectiveness of this remedy.

Eliminated

TECHNOLOGY PROCESS OPTION FOR GROUNDWATER

RETAINED/ELIMINATED

Enhanced In-Situ Biodegradation: To combine extraction and biological technologies, a modified groundwater pump-and-treat system is implemented whereby oxygenated water is circulated through the affected aquifer zone to enhance in-situ biodegradation of organic constituents. Enhanced biodegradation is most successful at sites with low concentrations of organics in the dissolved phase, little or no NAPL, and high aquifer transmissivity ($> 10^{-4}$ cm/s). Although the constituents of concern found at the Bldg. 735 site are known to be aerobically biodegradable, aquifer heterogeneity, low transmissivity, and NAPL presence may limit the effectiveness of this remedy. In addition, a full-scale enhanced in-situ biodegradation system would probably shut-down any on-going natural anaerobic biodegradation processes.

Eliminated

Hydraulic Containment: This remedy involves the installation of a limited number of groundwater extraction wells for the purpose of preventing migration of dissolved or free-phase constituents. Since the groundwater plume is relatively stable, and possibly shrinking due to biodegradation, this remedy would not provide additional benefits at the Bldg. 735 site.

Eliminated

Physical Containment: This remedy involves construction of an impermeable barrier (such as a slurry wall) around an affected groundwater zone, combined with long-term groundwater monitoring. Typically, physical barriers have not proven successful for stand-alone containment of dissolved constituents due to deterioration of barriers over time permitting leakage of contaminants. This remedy would be less effective at the Bldg. 735 site since the groundwater plume is restricted to a limited area, and the plume appears to have stabilized.

Eliminated

TECHNOLOGY PROCESS OPTION FOR SOILS

RETAINED/ELIMINATED

Institutional Controls: This remedy invokes some type of restriction to acceptable uses for affected property, such as deed restrictions, use restrictions, access control, contractual agreements, etc. For the Bldg. 735 site, institutional controls would focus on adherence to health and safety plans for construction in affected soil areas.

Retained

Bioventing: Bioventing is the process of applying air or oxygen to soil to stimulate the aerobic biodegradation of contaminants in: 1) the vadose zone, 2) the capillary fringe, and 3) saturated zones which have been dewatered. Bioventing is less effective in areas with a high water table, saturated soil lenses, or low aquifer permeability. Although the Bldg. 735 site exhibits many of these conditions, bioventing is still one of the most effective methods for extracting organic contaminants. Performance data after two years of operating the existing 8-well bioventing system indicates definite mass removal from the unsaturated soils, leading to the retention of this technology.

Retained

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TECHNOLOGY PROCESS OPTION FOR SOILS	RETAINED/ELIMINATED
<i>Aquifer Dewatering/Soil Vapor Extraction:</i> This combined soil/groundwater remedy involves the installation of recovery wells with drop tubes connected to vacuum headers; installation of a skid-mounted vacuum system for combined water and vapor extraction; and treatment of collected groundwater and vapors. Although low aquifer transmissivity may limit the rate of fluid and vapor extraction from the silty clay unit underlying the Bldg. 735 site, this approach is generally more effective in terms of organic mass removal than either groundwater pump-and-treat or in-situ biodegradation systems. This approach incurs high capital costs, but the technology is proven and is easily implementable.	<i>Retained</i>
<i>Limited Source Excavation:</i> Under this remedy, limited excavation of contamination in unsaturated soils is performed in tandem with some type of soil disposal or treatment technology. The most probable soil treatment scenarios include off-site disposal or Low Temperature Thermal Desorption (LTTD). While this technology is readily implementable, the cost associated with this approach do not match its effectiveness (i.e. low benefit to cost ratio).	<i>Eliminated</i>
<i>Extensive Excavation with Low Temperature Thermal Desorption;</i> This remedy involves excavation of all contaminated soils to background levels. Low Temperature Thermal Desorption (LTTD) and off-gas treatment would be required for soils removed from the site. At this site, the area of soil contamination is extensive, making this alternative both expensive and inefficient. Additionally, this alternative may not be implementable without some dewatering of the aquifer to prevent excavation in the saturated zone.	<i>Eliminated</i>
<i>Soil Flushing;</i> This remedy involves the injection of water containing an additive (such as surfactants or detergents) into the soil or groundwater to enhance the dissolution rate of residual NAPL. Contaminants which are dissolved into the injection fluid are collected, separated and treated. At the Bldg. 735 site, high site cleanup standards, experimental nature of the technology, and low aquifer permeability, eliminate this technology.	<i>Eliminated</i>

5.4 Potential Remedial Alternatives

5.4.1 Development of Alternatives

Based on the preliminary screening of remediation technologies, the following five technology process options have been retained as potentially capable of achieving remedial action objectives for the Bldg. 735 site:

- Natural Attenuation
- Institutional Controls
- Air Sparging
- Aquifer Dewatering/Soil Vapor Extraction
- Bioventing

These technologies have been combined into three remedial alternatives that address each of the general response actions identified in Section 5.3.2:

REMEDIAL ALTERNATIVE
Natural Attenuation of Groundwater Institutional Controls for Soil
Natural Attenuation of Groundwater Continued Operation of Existing Bioventing/Air Sparging System
Aquifer Dewatering/Soil Vapor Extraction System for Remediation of Affected Groundwater and Soils

Alternative 1-Natural Attenuation with Institutional Controls

Based on the risk assessment (Section 4), natural attenuation alone will effectively reduce dissolved contaminant concentrations at the Bldg. 735 site to below cleanup standards within 10 - 25 years. This approach would require the designation of sentry wells outside the current limits of the affected groundwater zone to monitor plume migration. Within the plume area, monitoring of the natural attenuation process would be conducted to ensure remediation progress.

In the affected soils area, institutional controls would be implemented. Such controls might require that any construction activities in the affected soil area (see Figure 5.1) be performed under a Health and Safety Plan that would address possible exposure to workers via inhalation, dust ingestion, and dermal contact. In all probability, this would mean that all construction in this area would be

subject to vapor monitoring and possible Level "B" Personal Protective Equipment.

Alternative 2 - Natural Attenuation and Continuation of In-Situ Bioventing /Air Sparging System

The second alternative is based on the continued use of the existing in-situ bioventing system installed at the Bldg. 735 site in late 1993 (Engineering-Science, 1993). Performance data collected following one year of operation indicates active remediation of unsaturated soils at the site. In addition, some oxygenation of the groundwater at the site has been observed (Engineering-Science, 1995). Continued operation of the system for an additional 1-5 years (depending on performance results) should provide substantial contaminant mass reduction in the unsaturated zone.

Note that natural attenuation would also be a factor in site remediation under this alternative as biodegradation processes would continue under operation of the bioventing/air sparging system. As such, this alternative would also include an aggressive groundwater monitoring program.

Alternative 3 - Aquifer Dewatering/Soil Vapor Extraction

The third alternative, aquifer dewatering/soil vapor extraction (AD/SVE) has been retained as a technology-intensive alternative. AD/SVE would allow for cleanup of the affected media to site remedial goals in a shorter period of time (approximately 5-10 years) than natural attenuation alone. AD/SVE requires a substantial initial investment in groundwater and vapor extraction and treatment equipment. Additional requirements must be met to appropriately dispose of treated water and vapors.

5.4.2 Description of Retained Alternatives

To facilitate selection of the optimal remediation strategy for the Bldg. 735 site, preliminary engineering designs and cost estimates have been developed for the three alternatives. General system layouts for each alternative are illustrated on Figures 5.1 - 5.3. Estimated capital and operations and maintenance (O&M) costs for each alternative are shown on Tables 5.2 through 5.4. Life-cycle costs for each alternative, based on capital expenditures and net present value of O&M costs, are presented on Table 5.5.

Alternative 1: Natural Attenuation with Institutional Controls

The natural attenuation alternative requires implementation of a long-term monitoring plan for groundwater and institutional controls for soil. Details on the monitoring program, institutional controls, and costs for this alternative are discussed below.

Monitoring Program; The monitoring program will involve sampling and analysis of three "sentry" wells and nine monitoring wells. The sentry wells are designed to serve as triggers, such that if concentrations of BTEX above site cleanup standards are observed then additional remediation responses may be implemented. For the Bldg. 735 site, three of the monitoring wells (MW-4, MW-5, and MW-6) installed during this investigation will be designated as sentry wells since they are downgradient of the groundwater contaminant plume, upgradient of the receptor, and they tested clean for BTEX during the field investigation. As shown in Figure 5.1, these wells are located between the observed groundwater plume and the drainage ditch that is approximately 100 ft downgradient of the leading edge of the plume.

Seven shallow monitoring wells will also be included in the long-term monitoring program under the Natural Attenuation alternative to verify the natural attenuation processes and to ensure no offsite migration of the plume. These monitoring wells include MW-1, 2, 3, 7, 8, and GMW-2, 3. In addition, the single deep well, MW-10, will be monitored to verify results from the vertical migration analysis (Section 3.2.6), and well GMW-1 will be monitored for representative background concentrations.

The long-term monitoring program under this alternative will include two separate sampling and analysis cycles. The sentry wells and nine monitoring wells will be sampled every quarter for the first year and annually every year thereafter until the groundwater plume dissipates. During the first year of monitoring, samples will be analyzed for the constituents of concern (BTEX) only. Subsequent sampling events will consist of BTEX samples every year supplemented by monitoring of the entire natural attenuation field program at years 1, 5, 10, and 15, if necessary. This natural attenuation sampling program will include all of the electron acceptors (dissolved oxygen, nitrate, sulfate, iron, and methane) and other parameters required to evaluate the progress of the natural attenuation process.

Institutional Controls; To protect construction workers, a site-specific Health and Safety Plan will be required for all construction activities occurring at the site while contaminated unsaturated soil contains benzene above 9.2 mg/kg. To be

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conservative, the entire area of contaminated soil has been designated as the area requiring controls (see Figure 5.1). These controls would be required until additional sampling indicates that benzene concentrations in soil at the site are below 9.2 mg/kg.

Note that if this area of the base is still under Air Force or Reserve control, then these restrictions could be implemented relatively easily, particularly because the area would not be accessible to the general public. If the land eventually is to be transferred, then some type of deed restriction or contractual language would be required to ensure that these institutional controls remain in place.

Life-Cycle Cost; The estimated life-cycle cost for this alternative, representing the total capital and O&M costs evaluated at net present value for an estimated lifetime of 15 years, is detailed on Table 5.2.

Alternative 2 - Natural Attenuation and Continuation of Bioventing /Air Sparging System

Bioventing/Air Sparging System; Alternative 2 requires that the existing 8-well bioventing/air sparging system continue to operate for an additional 1-5 years. This system utilizes wells screened to a depth of 11-ft to inject air into the unsaturated zone which partially depresses the water table. In addition this system also introduces dissolved oxygen into the saturated zone via air sparging.

As described above, the performance data from this system indicates active BTEX removal from the unsaturated soils, and some possible beneficial effects in the groundwater system. The performance data indicates definite biological activity (oxygen uptake in respiration test) in the unsaturated zone and an overall reduction in soil BTEX concentrations from the limited soil sampling that was performed. Keeping the system running, therefore, is beneficial to remediation of the unsaturated soils.

The effects of air sparging on groundwater are more difficult to interpret, as there is a definite increase in dissolved oxygen concentrations in GMW-3, but also direct evidence of strong anaerobic activity (high methane concentrations), as illustrated in the table below.

Indicator	10/22/93*	12/10/93	3/11/94	11/17/94
Dissolved Oxygen Concentration (mg/L)	0.09	0.36	7.05	3.4
Methane Concentration (mg/L)	N.M.	N.M.	N.M.	180

* Prior to Start-up of bioventing/air sparging system. N.M. = Not Measured.
(Engineering-Science, 1995)

Methanogens, which are representative of anaerobic conditions, are not active in aerobic environments since they are particularly intolerant of oxygen. It is difficult to determine which process (aerobic or anaerobic biodegradation) is removing more BTEX, since a simple mass balance on the oxygen and BTEX does not account for the rate that oxygen is being transferred by the air sparging system. Additional work would be required to more accurately assess the full benefits of the air sparging system for groundwater remediation.

Natural Attenuation; This alternative includes on-going natural attenuation for contaminated groundwater located outside the bioventing area (see Figure 5.2). The same groundwater monitoring plan described in Alternative 1 would be conducted, along with periodic performance monitoring of the bioventing/air sparging system. Based on engineering judgment, remediation of the groundwater plume would require 10-25 years (assuming worst-case no benefit from air sparging) while the bioventing system would continue to remove organics at an effective rate for another 1-5 years. The actual duration required for the bioventing system would be determined by periodic performance monitoring of conditions in the unsaturated zone.

Life-Cycle Cost; Capital costs for this alternative are zero since the system has been installed and is presently in operation. O&M costs are based on system operating expenses, such as operator expenses, general system maintenance and energy costs, and long-term monitoring costs. Capital and O&M costs for this alternative are presented on Table 5.3.

Alternative 3: Aquifer Dewatering/Soil Vapor Extraction

Aquifer Dewatering/Soil Vapor Extraction System; To evaluate a faster remediation approach, an intensive groundwater and soil remediation alternative was developed based on aquifer dewatering/soil vapor extraction (AD/SVE) processes. With this option, a single skid-mounted high-capacity vacuum pump is used to extract both groundwater and air from the subsurface. The system is designed to dewater the aquifer and utilize an induced air stream

to volatilize organics and deliver oxygen to the subsurface, enhancing aerobic biodegradation of BTEX components.

Extraction wells would be completed throughout the upper silty till aquifer in order to remediate both groundwater and soil simultaneously. A system of 12 groundwater/soil vapor extraction wells with 12 air inlet wells has been specified in this conceptual design to achieve site remediation in an estimated 5 to 10 year operating period. The preliminary well and treatment system locations developed as part of the conceptual design are shown on Figure 5.3.

Contaminated groundwater and soil vapors produced by the aquifer dewatering/soil vapor extraction system will require subsequent treatment and/or disposal. A modular treatment system to treat affected groundwater and off-gases is included in this alternative to ensure destruction of contaminants. Water will be sent through a shallow-tray air stripper, and produced vapors are to be treated using a catalytic thermal oxidizer. Based upon measured water quality data, groundwater produced by the remediation system described above is expected to contain the principal dissolved organic constituents, BTEX.

Life-Cycle Cost; Capital costs for this alternative include installation of SVE and vent wells, design and construction of a modular treatment system, and purchase of major equipment items. O&M costs are based on system operating expenses, such as operator expenses, general system maintenance and energy costs, and long-term monitoring costs. Capital and O&M costs for this alternative are presented on Table 5.4.

5.5 Detailed Analysis of Alternatives

The detailed analysis of alternatives provides the design information required to select the optimum remedy or remedies for a site. As described above, engineering conceptual designs were developed for each of the retained alternatives. To be retained for further analysis, each conceptual design was evaluated initially on the two *threshold criteria* specified in the FS guidance: overall protection of human health and the environment and compliance with existing regulations. Next, five *balancing criteria* are to be applied: long-term effectiveness and permanence; reduction of toxicity, mobility, or volume; short-term effectiveness; implementability; and cost. Finally, two *modifying criteria* will also be applied (state acceptance and community acceptance) following regulatory response to finalize selection of the most appropriate remedial alternative. These criteria are described in more detail below.

CATEGORY	EVALUATION CRITERIA
<i>Threshold Criteria</i>	<ul style="list-style-type: none"> • <i>Overall Protection:</i> Achievement and maintenance of protection for human health and the environment. • <i>Regulatory Compliance:</i> Conformance with chemical-, action-, and location-specific ARARs.
<i>Primary Balancing Criteria</i>	<ul style="list-style-type: none"> • <i>Long-Term Effectiveness and Permanence:</i> Magnitude of residual risk following remedy implementation; adequacy and reliability of controls for management of waste residues or untreated affected media. • <i>Reduction of Toxicity, Mobility, or Volume:</i> Degree to which containment and/or treatment technologies permanently reduce toxicity, mobility, or volume of hazardous substances. • <i>Short-Term Effectiveness:</i> Protection of community, workers, and environment during construction and implementation of the containment alternative; time required to achieve remedial action objectives. • <i>Implementability:</i> Technical feasibility (constructability, reliability, operability, and monitoring) considerations of containment remedies; availability of services and materials; administrative feasibility. • <i>Cost:</i> Capital cost; annual operating and maintenance expense; present worth analyses.
<i>Modifying Criteria</i>	<ul style="list-style-type: none"> • <i>State Agency Acceptance:</i> Compliance of containment remedy with state technical and administrative issues. • <i>Community Acceptance:</i> Degree to which alternative addresses issues of concern to the local community.

Evaluation criteria were applied in accordance with the general procedures of RI/FS guidance. Each alternative was found to satisfy the basic Threshold Criteria. Technical evaluation of each alternative will be based principally on the Primary Balancing Criteria. Cost estimates developed for this purpose will include both direct and indirect capital and operating/maintenance (O & M) costs. Present worth costs will be calculated for the estimated operating periods. Factors that may affect the accuracy of the cost estimates, such as effective life of the remedy, O & M costs, duration of cleanup, volume of affected materials, key design parameters, and discount rates, were considered in the estimating process. Table 5.6 shows the resulting overall evaluation rating, based on a scale from 0 to 9 points. The following sections discuss each alternative as it applies to the nine criteria.

5.5.1 Alternative 1 - Natural Attenuation with Institutional Controls

Natural attenuation with institutional controls provides adequate protection of human health and the environment, meets regulatory cleanup requirements, provides long-term effectiveness and permanence (following completion of natural attenuation processes), and reduces the toxicity, mobility and volume of groundwater contamination at the Bldg. 735 site. In the Treatability Study, the maximum extent of plume migration was estimated to ensure that potential receptors are not exposed to hazardous constituents while the affected media are undergoing natural attenuation. Modeling results and other evidence verify that contaminants are being destroyed by natural biodegradation processes, and the rate of the biodegradation process is predicted to be fast enough to prevent further plume migration.

Alternative 1 provides poor short-term effectiveness during the implementation phase due to the need for strict adherence to institutional controls to ensure protection of workers, and time required for site cleanup (10 to 25 yrs). Natural attenuation with institutional controls provides a very implementable (no construction required), cost efficient alternative. This alternative incurs low life-cycle costs since capital costs are minimal, and O&M costs are limited to long-term monitoring and reporting requirements. Life-cycle costs for this alternative are estimated to be approximately \$165K. The overall evaluation rating for this alternative is 6.0 points.

5.5.2 Alternative 2 - Natural Attenuation with Continuation of Bioventing/Air Sparging System

Alternative 2 provides adequate protection of human health and the environment, meets regulatory cleanup requirements, provides long-term effectiveness and permanence, and reduces the toxicity, mobility and volume of groundwater contamination at the Bldg. 735 site (see Table 5.6). Additionally, the bioventing/air sparging system definitely increases the rate of soil biodegradation at the site, and may reduce groundwater remediation times via oxygen addition. Because strong anaerobic processes were observed in groundwater, and because the highest soil contamination was below the observed water table, the overall effects of the bioventing/air sparging system on groundwater may be minimal, however.

This alternative rates highly on implementability since the bioventing/air sparging system is already in place, and moderate on cost due to annual system operations and maintenance costs that are incurred. Also, similar to Alternative 1, this alternative rates moderate on short-term effectiveness due to the lengthy

time required for groundwater cleanup (10 to 25 yrs). Life-cycle costs for this alternative are estimated to be approximately \$230K. The overall rating for this alternative is also 6.0 points.

5.5.3 Alternative 3 - Aquifer Dewatering/Soil Vapor Extraction

Alternative 3, aquifer dewatering/soil vapor extraction, similar to the other two alternatives, is protective of human health and the environment, meets regulatory cleanup requirements, provides long term effectiveness and permanence, and reduces the toxicity, mobility and volume of groundwater contamination at the Bldg. 735 site (refer to Table 5.6). This alternative rates moderate on short term effectiveness due to increased exposure of site personnel and workers to contaminant vapors during system operation. This alternative does, however, provide improved short-term effectiveness since the time required to achieve remedial action objectives is approximately 5 to 10 years. This alternative rates moderate for implementability since a large remediation system would need to be installed at the Bldg. 735 site, causing inconvenience and potential exposure to soil and groundwater contamination to base personnel and workers. Finally, this alternative rates poor on the cost evaluation due to the extensive capital costs required to install the system, and the high O&M costs required to manage the system over the duration of the project. Life-cycle costs for this alternative are estimated to be approximately \$830K. The overall rating for this alternative is 5.0 points.

5.5.4 Comparative Analysis

Each of the alternatives has been evaluated against the nine EPA RI/FS evaluation criteria and deemed to be appropriate for application at the Bldg. 735 site. In the comparative analysis, alternatives are evaluated against each other to provide information which will help determine which alternative should be selected for implementation. The comparative advantages and disadvantages of each alternative under each of the nine evaluation criteria is presented below:

Overall Protection of Human Health and the Environment: Each of the three alternatives provide protection of human health and the environment during remediation. In Alternatives 1 and 2, control of the groundwater migration pathways are achieved through natural attenuation and the use of sentry wells. Risk of direct contact with contaminated soils is controlled through the implementation of institutional controls, restricting access to the site without proper protection. Alternative 3 contains and treats contaminated groundwater and soils by dewatering the aquifer, volatilizing BTEX constituents, and treating extracted water and vapors.

Compliance With Laws and Regulations: Based on the risk assessment performed as part of the Treatability Study, both Alternatives 1 and 2 meet risk-based cleanup levels for affected groundwater at the site. Under these two alternatives, institutional controls address soils with contaminant concentrations above soil cleanup standards. Significant permitting work may be required to discharge treated vapors and water produced using Alternative 3.

Long-Term Effectiveness and Permanence: All three alternatives provide long-term effectiveness and permanence. The residual risk resulting from contact or ingestion of groundwater following completion of clean-up under each alternative will be below the 10^{-6} risk level standard. Additionally, Alternative 3 would ensure elimination of risk due to soil exposure.

Reduction of Toxicity, Mobility, and Volume: Since it represents an active remediation process, Alternative 3 will provide the fastest reduction of toxicity, mobility, and volume. Alternatives 1 and 2 provide destruction of contaminants through natural processes, however, at a slower rate than Alternative 3.

Short-Term Effectiveness: Alternatives 1 and 2 provide for limited contact with affected media during implementation and provide a minimal amount of worker exposure. Alternative 3, although it provides a faster clean-up period (5 to 10 yrs vs. 10 to 15 yrs) increases the exposure to base personnel and workers at the site, thus increasing short-term risk during implementation of the remedy.

Implementability: Alternatives 1 and 2 are easy to implement since alternative 1 requires no equipment installation, and alternative 2 is already in-place and operating. Alternative 3 would cause inconvenience and potential exposure to soil and groundwater contamination to base personnel and workers during installation.

Cost Efficiency: Alternative 1 is non cost-intensive since no capital outlay is required and O&M costs consist only of long-term monitoring. Alternative 2 also appears cost efficient since the bioventing/air sparging system is already in place, making capital expenditures zero, and O&M costs are restricted to long-term monitoring and system operation and maintenance. Alternative 3 is technology intensive, thus imposing extensive capital costs and high costs for operation and maintenance (Refer to Table 5.5 for capital and O&M cost comparison).

Regulatory Acceptance and Community Acceptance: These two modifying criteria address regulatory comments following submittal of the Focused Feasibility

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Study, and issues and concerns the public may have regarding each of the alternatives. Therefore, evaluation of the alternatives based on these criteria is reserved.

5.6 Summary

Alternatives 1 and 2 achieved equivalent ratings in terms of the nine evaluation criteria, and either remedy appears to be a good candidate for implementation at the Bldg 735 site. Alternative 3, due to problems with implementability and high cost, is judged to be the least attractive remedy.

Treatability Study/Focused Feasibility Study

Building 735 Site, Grissom AFB, Indiana
Air Force Center for Environmental Excellence (AFCEE)

APPENDICES

- Appendix A: References
- Appendix B: Test Methods
- Appendix C: Modeling Natural Attenuation
- Appendix D: Slug Test Data and Results
- Appendix E: Baseline Exposure Assessment Procedures
- Appendix F: SPL Environmental Laboratory Reports (not included with this submittal)

APPENDIX B TEST METHODS

Treatability Study/Focused Feasibility Study

Building 735 Site, Grissom AFB, Indiana

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B.0 TEST METHODS

B.1 Sampling and Analytical Procedures

The sampling program and rationale, analytical procedures, and general QA/QC protocol followed during the simulation study field investigation were detailed in Appendix B of the Treatment Study/Test Design (TSTD) for the Building 735 site, Grissom AFB, dated September 28, 1994. The sampling and analytical procedures were designed to meet the objectives of the simulation of natural attenuation program, and were generally conducted in accordance with the AFCEE Protocol guidelines (Wiedemeier *et al.*, 1994). The following sections contain a summary of the sampling and analytical procedures followed at the Bldg. 735 site.

B.1.1 Soil Investigation

The purpose of this drilling and soil sampling program was to 1) further characterize source area conditions, 2) confirm the locations of suspected source areas, and 3) delineate the vertical and horizontal extent of Chemicals of Concern (COC). For the simulation of natural attenuation study, 14 soil borings were drilled (thirteen to a depth of 15 feet and one to 30 ft below ground surface), at the locations shown on Figure B.1. Monitoring wells were subsequently installed in ten of these boring locations.

The soil borings were drilled using hollow-stem auger drilling methods, which minimized the introduction of drilling fluids to the subsurface and allowed visual identification of the uppermost water-bearing unit beneath the site. The soil borings were sampled continuously using a 5-foot core barrel, and were logged by a qualified geologist in accordance with the Unified Soil Classification System (USCS, shown on Figure B.2). At least one grab sample was collected every two feet to the total boring depth, split in half and placed in two separate containers. One half of the sample was placed in a jar, sealed, and retained for possible COC laboratory analysis; the other half of the sample was quickly transferred to a glass jar, sealed with aluminum foil, and held for 15 minutes at ambient temperature for measurement of volatile organic compounds (VOCs). The VOC measurement was made by puncturing the aluminum foil seal with a Photoionization Detector (PID) vapor probe, and reading the total concentration of the headspace gases, as related to an isobutylene calibration standard. Log of boring diagrams for the soil borings and monitoring wells are shown on Figures B.3 through B.16.

The soil samples were examined in the field for non-aqueous phase liquids (NAPLs) by 1) visual inspection, 2) broad wave spectrum UV fluorescence analysis, and 3) mixing with Sudan IV, a hydrophobic powder that dyes organic fluids red upon contact. Results of these tests are shown on the log of boring diagrams.

At each soil boring location, 1 to 3 soil samples (a total of 29) were selected for laboratory analysis based on visual observations and/or elevated PID readings, indicating the presence of organic constituents. Samples selected for laboratory analysis were delivered under chain-of-custody control to SPL Environmental Laboratories (SPL) within 24 hours of sample collection, and analyzed for the constituents indicated on Table B.1. Five samples were analyzed for particle size distribution (ASTM Method D422) by Fugro-McClelland (see Figure B.17 for results). In addition, 12 samples from the boring locations were selected for microbial assays by Retec, Inc., in order to establish the presence of an active microbial population within the saturated zone.

Upon completion, all soil borings not converted to monitoring wells were tremie-grouted to the surface with cement/bentonite grout. Following a period of at least 24 hours to allow for grout shrinkage, soil borings were topped off to ground surface with additional grout mixture. The grout consisted of Portland cement, with addition of 3-5% powdered bentonite clay by weight, thoroughly mixed with fresh water to form a smooth slurry. The soil borings were surveyed to the nearest 0.01 foot relative to the Indiana Coordinate System, East Zone, and the ground surface elevation of each location was determined to the nearest 0.01 foot relative to mean sea level by a registered public surveyor.

Borehole cuttings were contained in clean, 55-gallon DOT-approved drums and labeled as to source area, contents, boring number, date of collection, and name and telephone number of responsible party. At the completion of the drilling program, and after waste characterization, soil cuttings were disposed as non-hazardous at the Oak Ridge RDF waste management facility in Logansport, Indiana.

B.1.2 Groundwater Plume Delineation and Investigation

Monitoring Well Installation

In order to delineate the affected groundwater area within the Wisconsin water-bearing zone, ten monitoring wells were installed at locations shown

on Figure B.1. Nine of the wells were drilled to a depth of 15 ft, and one nested pair well was drilled to a depth of 30 ft below grade at the Bldg. 735 site. The nested pair was installed in order to investigate vertical COC distribution and vertical hydraulic gradient. Drilling of monitoring well borings was conducted in accordance with the procedures specified above in Section B.1.1. The wells were constructed of flush-threaded, 2-inch diameter, schedule 40 PVC casing, fitted with an approximate 10 ft length of No. 10 gauge slotted (i.e., 0.010-inch slot) schedule 40 PVC wellscreen and 2.5-ft casing blank sumps. A 10-ft length of screen was used rather than the 5-ft recommended by AFCEE guidelines (Wiedemeier *et al.*, 1994), in order to accommodate water level fluctuations of the shallow unconfined aquifer (reportedly from 0.1 ft to 9 ft below ground surface - Engineering-Science, 1993). Log of boring and as-built diagrams for the monitoring wells are shown on Figures B.3 through B.12.

The monitoring wells were all low yield and were developed by bailing to remove fine-grained materials and ensure an effective hydraulic connection with the permeable silt/clay unit. Well development proceeded until 1) the produced water was relatively free of fine particles, 2) at least ten well casing volumes had been removed, and 3) at least three successive, stabilized readings of pH, specific conductivity, and temperature had been obtained (i.e., readings which were separated by the removal of at least one well casing volume and which exhibited less than or equal to a 10 percent change in specific conductance, a 0.2 standard units change in pH, and a 1.0° F change in temperature).

For well protection, flush-grade well covers were installed at ground surface at all locations. Monitoring well locations were surveyed to the nearest 0.01 foot relative to the Indiana Coordinate System, East Zone, and the ground surface and top-of-casing elevation of each well was determined to the nearest 0.01 foot relative to mean sea level. All surveying was conducted by a registered public surveyor.

Field Plume Delineation

In order to delineate the affected groundwater area within the Wisconsin water-bearing zone, groundwater samples were collected from the monitoring wells after each well installation and analyzed in the field for organic indicator parameters with a Photovac 10S Plus Portable Gas Chromatograph. Based on the field test results, a decision was made on subsequent monitoring well locations.

Groundwater Sampling and Testing

Following a sufficient time period to allow equilibration of the new wells, static water level elevations were measured in the new wells and in the four existing monitoring wells at the Bldg. 735 site. Prior to sample collection, the wells were purged a minimum of three casing volumes of fluid to ensure collection of representative samples. Groundwater samples were collected from the wells; analyzed in the field for temperature, pH, dissolved oxygen, oxidation-reduction potential, and specific conductivity; and delivered under chain-of-custody control to SPL Environmental Laboratories (SPL) within 24 hours of sample collection. Collected samples were analyzed in the laboratory for the constituents indicated on Table B.1.

In order to determine the presence or absence of NAPLs within site monitoring wells, a bailer was lowered to the top of the water zone, retrieved, and checked for evidence of NAPL presence by 1) visual inspection, 2) using an interface probe for direct hydrocarbon detection, and 3) mixing with Sudan IV dye.

All groundwater produced during development and sampling was transported for disposal in the oil-water separator located at Building 21 at Grissom AFB.

Slug Tests

In order to determine the hydraulic conductivity of the Wisconsin water-bearing zone, a double slug test consisting of a rising-head slug test followed by a falling-head test was conducted at five locations (i.e., at four shallow monitoring wells and one deep well) in accordance with AFCEE guidelines (Wiedemeier *et al.*, 1994). The slug tests were accomplished by rapidly removing or introducing a solid PVC slug of a known volume, and then allowing the water level to stabilize while taking water level measurements at closely spaced time intervals. The water levels were measured with electronic pressure transducers installed within the monitoring wells, and recorded using an Instrumentation Northwest Aquistar DL-8A Datalogger. Results of the slug tests are summarized on Table 2.2, detailed test results are included in Appendix D of this report.

B.1.3 Sampling Equipment and Procedures

Equipment Decontamination Procedures

Equipment employed during drilling, sampling, and monitoring well installation was decontaminated prior to use at the site. Initial decontamination procedures consisted of a high-pressure hot water or steam wash with a non-phosphate detergent, followed by a rinse with potable water. The downhole portions of drilling equipment and sampling tools were similarly decontaminated between all drilling locations.

If re-used, soil sampling devices were decontaminated after each usage to ensure that only clean sampling tools were employed during sample collection. Sampling devices were decontaminated with a triple non-phosphate detergent wash followed by a triple rinse with distilled water.

Groundwater sampling equipment was decontaminated in accordance with guidelines discussed below. Prior to leaving the site, all drilling and sampling equipment were decontaminated at the temporary site decontamination station.

General Procedures for Handling and Collection of Soil Samples

General procedures used for the collection and handling of soil samples were as follows:

- 1) To the extent possible, locations were sampled in order of increasing contaminant concentration in order to minimize potential for cross-contamination.
- 2) Soil samples were handled only with clean gloves and sampling tools. Gloves were changed between sampling locations.
- 3) Soils were logged in accordance with the Unified Soil Classification System (USCS), and other relevant features, such as qualitative moisture content and presence or absence of chemical staining or hydrocarbon odor, were noted.
- 4) The outer surface of soil cores collected using tube samplers were trimmed using a clean knife prior to packaging for shipment to the laboratory to ensure that soils which had been in contact with formation

fluids above the sample point, or with the inside wall of the sampler, were not tested.

- 5) Soil samples were collected in clean glass jars with tight-fitting lids, and identified with appropriate labels. All samples collected from the Bldg. 735 site as part of the Natural Attenuation project were labeled in accordance with the sample labeling system described on Figure B.4 of the TSTD. Sample labels included sample designation, sample location, date and time of collection, and collection personnel.
- 6) Soils to be analyzed for volatile organic compounds were placed in appropriate sample containers with minimum head-space. All samples were preserved on ice for shipment to the laboratory within 24 hours of collection.

General Procedures for Handling and Collection of Groundwater Samples

General procedures for the handling and collection of groundwater samples are listed below:

- 1) A site wide static water level survey was conducted prior to well purging and sample collection. Static water levels were measured with a clean electronic water level indicator in all existing wells at the Bldg. 735 site during the sampling episode. Results of the water level surveys are shown on Table 2.1.
- 2) At each location where groundwater was sampled, a minimum of three casing volumes of groundwater were purged within 24 hours prior to sample collection. Prior to purging, the static water level and the bottom of the well were measured to the nearest 0.01 foot using a clean static water level indicator.
- 3) All sampling equipment that contacted the groundwater sample was thoroughly cleaned before use in accordance with the following protocol:
 - Clean with potable water and phosphate-free detergent;
 - Rinse with distilled or deionized water;
 - Clean with distilled or deionized water and phosphate-free detergent;
 - Triple rinse with distilled or deionized water;

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When pre-cleaned dedicated sampling equipment was used (e.g., dedicated bailers, tubing for peristaltic pumps, etc.), the cleaning protocol specified above was not required. Dedicated Teflon bailers were used for all groundwater sampling.

- 4) To the extent possible, well locations were sampled in order of increasing groundwater constituent concentrations in order to minimize potential for cross-contamination.
- 5) Groundwater sampling equipment and containers were handled only with clean latex or neoprene gloves. Gloves were changed between sampling locations.
- 6) Groundwater was collected as needed to fill the appropriate laboratory sample containers for the groundwater sampling parameters listed on Table B.1.
- 7) Additional groundwater was collected for immediate analysis of temperature, pH, dissolved oxygen, oxidation-reduction potential, and specific conductivity at the well site.

Sample Preservation and Shipment

All samples selected for laboratory analysis were prepared for shipment as follows:

- Sample jar, bottle, or vial was sealed securely.
- Label showing sample number and sample source, sampler's initials, and the date and time of sample collection was attached on sample container.
- All pertinent information was entered on the field data sheets, and chain of custody/laboratory request form. The chain-of-custody/laboratory request form accompanied the samples throughout all phases of shipment and handling.
- Samples were transported in ice chests containing an adequate volume of ice to maintain samples at a temperature of 4° C until received by laboratory.
- Samples were transported directly to lab, or to courier for delivery to lab, within 24 hours of sample collection.

Analytical Testing Program

A summary of the analytical program for soil and groundwater samples collected in the Natural Attenuation project is provided on Table B.1 of this report. Tables B.3 and B.4 of the TSTD provided the sample container and preservation requirements associated with each laboratory test. Detailed information on the laboratory quality control/quality assurance evaluation is included in Section B.2, below.

B.2 Laboratory Data Validation Summary

B.2.1 Project Data Quality Objectives

Soil and groundwater samples collected during the period of October to November 1994 were submitted to SPL Environmental Laboratories (SPL) for analysis. The results of these analyses are shown on Tables 2.3 through 2.7 of this report. These data were used to further characterize the site, to assess the effectiveness of natural attenuation at the site, and to model contaminant fate and transport using the BIOPLUME II model.

To ensure that data generated from this project would be valid, defensible, and of known precision and accuracy, a Quality Assurance Project Plan (QAPP) was prepared as part of the TSTD Workplan for the Building 735 site at Grissom AFB. The QAPP set forth quality assurance (QA) and quality control (QC) procedures to be implemented during the sampling and analysis activities of this investigation. A formal data validation was conducted to verify that all QA/QC procedures were followed and that statistical control was maintained during the laboratory analysis of samples. As described in the QAPP, QA objectives for accuracy, precision, completeness, representativeness, and comparability were considered during the data validation process. Data validation parameters and results are outlined below.

B.2.2 Data Validation Assessment Parameters and Results

The following QA/QC parameters were used to validate all analytical data submitted by SPL for soil and groundwater samples collected at the Bldg. 735 site. The criteria for assessing these parameters were based upon QA/QC

requirements detailed in the *AFCEE Handbook for the Installation Restoration Program (IRP)*, in addition to method-specified requirements. The assessment parameters and results of this data validation are discussed below and are summarized on Tables B.2 and B.3 of this appendix.

Field Quality Control

Chain of custody records were reviewed to verify that the frequency requirements were met for trip blanks, sample duplicates, and equipment blanks. The following frequencies for these field control samples were specified in the QAPP:

<u>QC Parameter</u>	<u>Analytes Tested</u>	<u>Frequency</u>
Trip Blanks	BTEX Compounds	1 per day
Equipment Blanks	All COCs	1 per day*
Duplicates	All COCs	1 per 10 groundwater samples 1 per 10 soil samples

*Only if no dedicated sampling equipment used.

The analytical results of field duplicates and blanks were reviewed to assess sampling precision and the potential for sample contamination, respectively.

Groundwater Analyses: No equipment blanks were collected because dedicated equipment was used at each sampling location.

Trip blanks were submitted for analysis on each day of sampling with one exception: no trip blank was submitted with groundwater samples GMW-1 and GMW-4 collected on November 18, 1994. The analytic results for volatile organic compounds for these two samples, however, indicated no detectable concentrations for any of the target analytes. Volatile organics were below the detection limit in all of the six trip blanks analyzed.

The frequency requirement for the collection of groundwater duplicates was met: fourteen groundwater samples and two duplicates were submitted for

analysis. The following equation was used to compute the relative percent difference between a duplicate set of analyses:

$$RPD = 100 \times \frac{|x_1 - x_2|}{\left(\frac{x_1 + x_2}{2}\right)}$$

where: RPD = relative percent deviation, in percent,
 x_1 = the value for the first duplicate, and
 x_2 = the value for the second duplicate.

The relative percent difference among duplicate water analyses for total BTEX, total petroleum hydrocarbons (TPH), lead, chloride, sulfate, nitrate, and total dissolved solids were computed. The results averaged 15.3%, indicating acceptable sampling precision.

Soil Analyses: The frequency requirement for duplicate soil samples (10% of soil samples) was not met. Twenty-nine soil samples and two duplicate soil samples were collected from the Bldg. 735 site. This discrepancy was noted after completion of the sampling program. Corrective measures have been taken by the consultant project manager to prevent the recurrence of this problem (see Corrective Actions section below).

The average relative percent difference between soil duplicate sets for total BTEX, TPH, and lead analyses was 24%, indicating acceptable sampling precision.

Chain of Custody Procedures

Records were reviewed to ensure that sample custody was properly documented with appropriate signatures. Proper storage of the samples during transit from field to lab was confirmed by the notation of sample integrity and temperature upon receipt by SPL. Field and laboratory sample identifications were checked to confirm reporting consistency. All chain of custody documentation complied with these validation criteria.

Holding Time

The elapsed time between field sampling and laboratory analysis dates were compared to method-specified holding times. All analyses were completed by the laboratory within holding time limits.

Laboratory Calibration Procedures

Run logs, raw data (including chromatograms and quantitation reports), and calibration summaries provided by SPL were reviewed to verify that the initial calibration included at least five standards with response factors having a relative standard deviation of less than 20%. Laboratory verification of quantitation limits was confirmed when the most dilute calibration standard contained all analytes of interest at a concentration below the practical quantitation limit. The reported frequency of continuing calibrations were checked to ensure that at least one mid-concentration standard was run each day, or for every twenty samples, whichever was more frequent. These requirements for initial and continuing calibrations were met for all analyses conducted on soil and groundwater samples collected at the Bldg. 735 site.

Laboratory Quality Control

Laboratory Control Sample Frequency Requirements: Laboratory documentation was reviewed to confirm that, at a minimum, one method blank, one laboratory control sample (LCS), and one matrix spike/matrix spike duplicate set were tested for every twenty samples analyzed. These laboratory control sample frequency requirements, as well as the method specified requirements for surrogate analyses, were met.

Laboratory Control Sample Results: The results for method blank analyses were checked to identify potential sample contamination occurring in the laboratory. No target analytes were detected in any laboratory blanks analyzed as part of this program.

Analytical accuracy was assessed by comparing the recoveries of spiked compounds in the LCS and surrogate spikes to the control limits specified in the QAPP. These quality control criteria were met for all reported data included in this report. LCS percent recoveries were initially outside of control limits for TPH analyses on soil by EPA method 8015. The method was modified to omit concentrating the extracted sample and LCS recoveries were brought within control limits. Results reported in this document for soil and groundwater TPH were obtained under statistically controlled conditions and are, therefore, considered valid.

Matrix spike analyses were reviewed to identify matrix specific bias. As discussed in the *AFCEE Handbook for the Installation Restoration Program*, matrix specific bias is suspected when the percent recoveries for matrix spike

and matrix spike duplicate analyses are outside of control limits while the LCS recoveries are within control limits. The matrix spike percent recoveries for toluene, ethylbenzene, and xylenes were below the established control limits in four out of seven MS/MSD analyses conducted on soil samples from this site. The percent recoveries for the batch LCSs were within control limits, however, indicating statistical control and the possibility of matrix induced bias for these analytes.

Analytical precision (a measure of the reproducibility of data) was assessed by comparing the relative percent difference between matrix spike duplicates to the control limits specified in the QAPP. These quality control criteria were met for all analyses performed as part of this project.

Corrective Actions

Corrective action was taken and documented by SPL in response to LCS recoveries being out of control during Total Petroleum Hydrocarbon (TPH) analyses on site soil samples by EPA method 8015. The method was modified to omit concentrating the extracted sample and LCS recoveries were brought within control limits. Results reported in this document for soil and groundwater TPH were obtained under statistically controlled conditions and are, therefore, considered valid.

As noted in the field quality control section above, the frequency requirements specified in the QAPP for trip blanks and soil duplicates were not met during the sampling program at the Bldg. 735 site. The following corrective measures have been taken by the consultant project manager to prevent the recurrence of this event: 1) the project QAPP was reviewed with all personnel conducting sampling, and 2) a policy has been established whereby the field geologist will fax the chain of custody forms to the consultant quality assurance manager to be checked for compliance with quality control sampling requirements the same day of sampling.

B.2.3 Data Validation Summary

The data validation procedure described above was conducted on all analytical data generated for this natural attenuation investigation and included in this report. All analyses were performed within holding time limits, and the data quality objectives established for analytical accuracy (assessed by the percent recoveries in the LCS and surrogate spike analyses) and for precision (assessed by the relative percent difference between matrix spike duplicates) were consistently met. Therefore, the completeness of this

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data, defined as the percentage of measurements performed that are judged to be valid measurements, is 100%.

Representativeness is a qualitative assessment of the degree to which environmental data truly represent the site characteristics or conditions being measured. Both field and laboratory blanks analyzed for this project indicate no sample contamination occurred during sampling or analysis. The relative percent difference between field duplicates indicate acceptable sampling precision. As stated above, all analytic results are considered valid, and the distribution of sampling locations appears to encompass the contaminated zone at this site. Therefore, the reported data may be considered representative of actual site conditions.

Comparability is a measure of the degree to which distinct data sets can be compared. The complete documentation of field sampling procedures provided with this report, the adherence by SPL to EPA method protocols (with the exception of the soil TPH analyses), and the use of conventional metric units supports the comparability of this data with other data which has been or may in the future be collected at the site.

APPENDIX C MODELING NATURAL ATTENUATION

Treatability Study/Focused Feasibility Study

Building 735 Site, Grissom AFB, Indiana

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C.0 MODELING NATURAL ATTENUATION

The Air Force/EPA Natural Attenuation Protocol includes groundwater modeling of the natural attenuation at sites in order to 1) determine if computer models can explain the observed distribution of contaminants, electron acceptors and metabolic byproducts, 2) estimate the extent of further plume migration and the time required to completely degrade the contaminants, and 3) estimate the risk to potential receptors and the resulting potential risk-based cleanup standards for the source zone. Efforts to develop contaminant transport models which simulate both aerobic and anaerobic biodegradation processes are currently underway. The following sections detail natural attenuation modeling approaches, including specific approaches developed as part of this project.

C.1 Biodegradation Modeling: The BIOPLUME II Model

Naturally occurring contaminant attenuation processes such as adsorption, dispersion, aerobic biodegradation, and anaerobic biodegradation can significantly enhance the rate of organic mass removal from contaminated groundwater aquifers. Biodegradation research performed by Rice University, the U.S. EPA, and other research groups has identified two main themes that are crucial for future studies of natural attenuation:

1. *The relative importance of groundwater transport vs. microbial kinetics is a key consideration for developing workable biodegradation expressions in models. Results from the United Creosote site (Texas) and the Traverse City Fuel Spill site (Michigan) indicate that biodegradation is represented better as a macro-scale waste water treatment-type process than as a micro-scale study of microbial reactions.*
2. *The hydrogeologic conditions at a site and the chemical(s) of interest determine the complexity of the biodegradation model needed. In many cases very simple kinetic models can be used to accurately simulate biodegradation, while in other cases more complex models are required.*

Rifai *et al.* (1989) developed the BIOPLUME II model, which simulates aerobic biodegradation as an instantaneous reaction between oxygen and organic contaminants in ground water. The USGS two-dimensional solute transport model (Konikow and Bredehoeft, 1978) was modified to simulate the transport of two plumes: an oxygen plume and a contaminant plume. The two plumes are allowed to react and the ratio of oxygen to contaminant consumed by the reaction is determined from an appropriate stoichiometric model. The BIOPLUME II model is documented with a detailed user's manual (Rifai *et al.*, 1987) and is currently being used by EPA regional offices, U.S. Air Force facilities, and by consulting firms. Borden *et al.* (1986) applied the BIOPLUME

concepts to the Conroe Superfund site; Rifai *et al.* (1989) and Rifai *et al.* (1991) applied the BIOPLUME II model to a jet fuel spill at a Coast Guard facility in Michigan. Many other studies using the BIOPLUME II model have been presented in recent literature.

The BIOPLUME II model has increased the understanding of biodegradation and natural attenuation by simulating the effects of adsorption, dispersion, and aerobic biodegradation processes in one model. It incorporates a simplified mechanism (first-order decay) for handling other degradation processes, but does not address specific anaerobic decay reactions. Early conceptual models of natural attenuation were based on the assumption that the anaerobic degradation pathways were too slow to have any meaningful effect on the overall natural attenuation rate at most sites. Accordingly, most field programs focused only on the distribution of oxygen and contaminants, and did not measure the indicators of anaerobic activity such as depletion of anaerobic electron acceptors or accumulation of anaerobic metabolic by-products.

C.2 The Air Force/EPA Natural Attenuation Initiative

Over the past several years, the high cost and poor performance of many pump and treat remediation systems has led many researchers to consider natural attenuation as an alternative technology for groundwater remediation. A detailed understanding of natural attenuation processes is needed to support the development of this remediation approach. Researchers associated with the U.S. EPA's R.S. Kerr Environmental Research Laboratory have suggested that anaerobic pathways could be a significant, or even the dominant, degradation mechanism at many petroleum fuel sites (Wilson, 1995). The natural attenuation initiative, developed by the Air Force Center for Environmental Excellence, is designed to evaluate anaerobic degradation at over 40 sites around the country and to develop modeling tools that simulate both aerobic and anaerobic biodegradation mechanisms and accurately predict the rate of attenuation occurring at contaminated sites.

The following sections summarize some of the key research findings of the Air Force/EPA Natural Attenuation Initiative that confirm the importance of anaerobic biodegradation in groundwater and demonstrate the effectiveness of natural attenuation at many sites.

C.3 Utilization of Different Electron Acceptors

In the presence of organic substrate and dissolved oxygen, microorganisms capable of aerobic metabolism will predominate over anaerobic forms. However,

dissolved oxygen is rapidly consumed in the interior of contaminant plumes, converting these areas into anoxic (low oxygen) zones. Under these conditions, anaerobic bacteria begin to utilize other electron acceptors to metabolize dissolved hydrocarbons. The principle factors influencing the utilization of the various electron acceptors include: 1) the availability of various electron acceptors at a particular site, and 2) the relative biochemical energy provided by the reaction.

C.3.1 Preferred Reactions by Energy Potential

Biologically mediated degradation reactions are oxidation/reduction (redox) reactions, involving the transfer of electrons from the organic contaminant compound to an electron acceptor. Oxygen is the electron acceptor for aerobic metabolism where as nitrate, ferric iron, sulfate, and carbon dioxide serve as electron acceptors for alternative anaerobic pathways. This transfer of electrons releases energy which is utilized for microbial cell maintenance and growth. The biochemical energy associated with alternative degradation pathways can be represented by the redox potential of the alternative electron acceptors: the more positive the redox potential, the more energetically favorable is the reaction utilizing that electron acceptor. Organisms with more efficient modes of metabolism grow faster and therefore dominate over less efficient forms. The relative redox potential and reaction preference for each electron acceptor is shown below:

Electron Acceptor	Type of Reaction	Metabolic By-Product	Redox Potential (pH = 7, in volts)	Reaction Preference
Oxygen	Aerobic	CO ₂	+ 820	<i>Most Preferred</i>
Nitrate	Anaerobic	N ₂ , CO ₂	+ 740	↓
Ferric Iron (solid)	Anaerobic	Ferrous Iron (dissolved)	- 50	↓
Sulfate	Anaerobic	H ₂ S	- 220	↓
Carbon Dioxide	Anaerobic	Methane	- 240	<i>Least Preferred</i>

Based solely on thermodynamic considerations, the most energetically preferred reaction should proceed in the plume until all of the required electron acceptor is depleted. At that point, the next most-preferred reaction should begin and continue until that electron acceptor is gone, leading to a pattern where preferred electron acceptors are consumed one at a time, in sequence. Based on these principles, one would expect to observe monitoring well data with "no-detect" results for the more energetic electron acceptors, such as oxygen and nitrate, in

locations where evidence of less energetic reactions is observed (e.g. monitoring well data indicating the presence of ferrous iron).

In practice, however, it is unusual to collect samples from natural attenuation monitoring wells that are completely depleted in one or more electron acceptors. Two processes are probably responsible for this observation:

- Alternative biochemical mechanisms having very similar energy potentials (such as aerobic oxidation and nitrate reduction) may occur concurrently when the preferred electron acceptor is reduced in concentration, rather than fully depleted. Facultative aerobes, for example, can shift from aerobic metabolism to nitrate reduction when oxygen is still present but in low concentrations (i.e. 1 mg/L oxygen; Snoeyink and Jenkins, 1980). Similarly, noting the nearly equivalent redox potentials for sulfate and carbon dioxide (-220 volts and -240 volts, respectively) one might expect that sulfate reduction and methanogenic reactions may also occur together.
- Standard monitoring wells, having 5 to 10 foot screened intervals, will mix waters from different vertical zones. If different biodegradation reactions are occurring at different depths, then one would expect to find geochemical evidence of alternative degradation mechanisms occurring in the same well. If the dissolved hydrocarbon plume is thinner than the screened interval of a monitoring well, then the geochemical evidence of electron acceptor depletion or metabolite accumulation will be diluted by mixing with clean water from zones where no degradation is occurring.

Therefore, most natural attenuation programs yield data that indicate a general pattern of electron acceptor depletion, but not complete depletion, and an overlapping of electron acceptor/metabolite isopleths into zones not predicted by thermodynamic principles. For example, a zone of methane accumulation may be larger than the apparent anoxic zone. Nevertheless, these general patterns of geochemical changes within the plume area provide strong evidence that multiple mechanisms of biodegradation are occurring at many sites.

C.3.2 Distribution of Electron Acceptors at Sites

As described above, the utilization of electron acceptors is generally based on the energy of the reaction and the availability of the electron acceptor at the site. While the energy of each reaction is based on thermodynamics, the distribution of electron acceptors is dependent on site specific hydrogeochemical processes and can vary significantly between sites.

For example, a study of five sites including the Grissom AFB Bldg. 735 site yielded the following summary of available electron acceptors and metabolic by-products. At the Patrick AFB site, nitrate and sulfate are not important electron acceptors while the oxygen and the methanogenic reactions dominate. At Hill

AFB, the sulfate reactions are extremely important because of the large amount of available sulfate for reduction.

Measured Electron Acceptor or By-Product Concentration (mg/L)					
Base Facility	Dissolved Oxygen	Background Nitrate	Maximum Ferrous Iron	Background Sulfate	Maximum Methane
POL Site, Hill AFB, Utah	6.0 *	17 *	50.5 *	98 *	2.0 *
Hangar 10 Site, Elmendorf AFB, Alaska	0.8 *	15 *	9.0 *	23 *	9.1 *
Site ST-41, Elmendorf AFB, Alaska	8.6 *	25 *	40.5 *	55 *	1.6 *
Site ST-29, Patrick AFB, Florida	3.7 *	0.30	1.9 *	10 *	15 *
Bldg. 735, Grissom AFB, Indiana	11.0 *	0.9	2.8 *	80 *	1.8 *

* Field data indicates electron acceptor utilization or by-product generation is occurring at site.

As indicated by these data, the degree of biodegradation depends on the type and amount of electron acceptors at a specific site.

C.4 Biodegradation Capacity

C.4.1 Utilization Factors

For a given background concentration of an individual electron acceptor, the potential contaminant mass removal or "biodegradation capacity" depends on the "utilization factor" for that electron acceptor. The utilization factor, defined as the mass of electron acceptor required to degrade a given mass of dissolved hydrocarbon, can be estimated from the stoichiometric equation for the degradation reaction. Dividing the background concentration of an electron acceptor by its utilization factor provides an estimate (in concentration units) of the assimilative capacity of the aquifer by that mode of biodegradation. Wiedemeier et al. (1994) suggest the use of the following utilization factors:

Electron Acceptor	Utilization Factor:
	Mass Electron Acceptor Consumed per Mass Dissolved Hydrocarbon Degraded
Oxygen	3.14 gm/gm
Nitrate	4.9 gm/gm
Ferric Iron	21.8 gm/gm
Sulfate	4.6 gm/gm
Carbon Dioxide	0.78 gm/gm

Note that while the utilization factors for oxygen, nitrate, and sulfate are very close in value, the background concentrations for nitrate and sulfate can be much greater than those seen for oxygen. Therefore, if not limited by kinetics, the combined assimilative capacity of an aquifer to degrade petroleum contaminants by anaerobic processes can far exceed the capacity due to aerobic mechanisms alone.

C.4.2 Calculation of Biodegradation Capacity

When the available electron acceptor/by-product data are divided by the appropriate utilization factor, an estimate of the biodegradation capacity can be developed. As shown by the following table, the biodegradation capacity and most important reaction varies from site to site:

Biodegradation Capacity (mg/L of Hydrocarbon)						
Base Facility	Aerobic Biodegradation	Nitrate Reduction	Iron Reduction	Sulfate Reduction	Methanogenesis	Total Biodegradation Capacity
POL Site, Hill AFB, Utah	1.9	3.5	2.3	21.3	2.6	31.6
Hangar 10 Site, Elmendorf AFB, Alaska	0.3	3.1	0.4	5.0	11.8	20.6
Site ST-41, Elmendorf AFB, Alaska	2.7	4.5	1.9	12.0	2.1	23.2
Site ST-29, Patrick AFB, Florida	1.2	0.1	0.1	2.2	19.5	23.1
Bldg. 735, Site, Grissom AFB, Indiana	2.8	0.16	0.05	13	1.23	17.3

Note: Values in **BOLD** represent electron acceptor with highest biodegradation capacity.

At each of these five sites, either sulfate reduction or methanogenesis appears to provide the highest potential degradation capacity for natural attenuation.

Extending the analysis further indicates that this capacity was utilized at these sites. A significant percentage of the sulfate was removed from the groundwater located inside the contaminant plume at the Hill AFB, Hanger 10, ST-41 site, and Bldg. 735 site, indicating a very active sulfate reduction reaction. High concentrations of methane were observed at a number of sites, indicating active methanogenic reactions.

Note that the sulfate and methanogenic reactions are the least energetic of all of the biologic reactions that are important to natural attenuation. These results indicate that it is relatively easy to deplete high energy electron acceptors (oxygen and nitrate) and initiate the low-energy ferric iron, sulfate, and methanogenic reactions. Because of the high utilization factor for ferric iron (21.8 mg of ferrous iron by-product is associated with the degradation of 1 mg of dissolved hydrocarbon), the iron reactions are of relatively minor importance at these sites, accounting for less than 1% of the total hydrocarbon degradation.

C.4.3 Actual Utilization of Different Electron Acceptors

Groundwater Services, Inc. (GSI) has evaluated the data from five sites, including the Building 735 site at Grissom AFB, to provide a quantitative estimate of the contaminant removal resulting from alternative degradation mechanisms at these sites. The areas between concentration contours were integrated to quantify the depletion of individual electron acceptors (oxygen, nitrate, and sulfate), and the accumulation of anaerobic metabolites (ferrous iron and methane) relative to background concentrations. These values were then divided by the electron acceptor utilization factor to estimate the contaminant mass destruction resulting from each alternative mode of metabolism. The table below summarizes the results of this study and shows the apparent relative contribution of each biodegradation mechanism to contaminant mass removal at each site.

While oxygen depletion was observed at every site, the contribution of aerobic processes to contaminant mass removal is relatively small. This is explained by the typically low concentrations of dissolved oxygen, compared to other electron acceptors. This analysis did not, however, account for reaeration from the vadose zone, and, therefore, potentially underestimates the contribution of aerobic oxidation.

Percent of Hydrocarbon Removed by Each Reaction (%)					
Base Facility	Oxygen Reduction	Nitrate Reduction	Iron Reduction	Sulfate Reduction	Methanogenesis
POL Site, Hill AFB, Utah	8	20	< 1	72	< 1
Hangar 10 Site, Elmendorf AFB, Alaska	3	26	1	32	38
Site ST-41, Elmendorf AFB, Alaska	6	26	1	32	38
Site ST-29, Patrick AFB, Florida	15	0	< 1	0	85
Bldg. 735, Grissom AFB, Indiana	12	0	< 1	87	1

Note: Values in **BOLD** represent electron acceptor with most important reaction.

Anaerobic processes appear to be very significant in contaminant mass removal at all sites. The data indicate that anaerobic or facultatively aerobic bacteria utilizing sulfate and nitrate reduction mechanisms accomplish the majority of contaminant mass removal at sites possessing high background levels of these electron acceptors (see Hill AFB and Elmendorf AFB).

The geochemical data for the ST-29 site at Patrick AFB, indicate extremely low background levels of nitrate and sulfate (below 0.3 and 10 mg/L, respectively), and show no evidence of nitrate or sulfate utilization. The data from this site demonstrated significant methane accumulation within the anoxic portion of the plume. Significant methane concentrations were also observed at the Hangar 10 Site at Elmendorf AFB within the anoxic and sulfate depleted portion of the plume. Limited evidence of methanogenesis was observed at Grissom AFB, and no evidence of methanogenesis was observed at Hill AFB. Possible reasons include: 1) there was still sulfate available in the middle of the plume (>20 mg/L), making sulfate reduction the preferred reaction, 2) kinetic constraints of methanogenic reactions may limit their expression at sites, such as Hill AFB, which have relatively short hydraulic residence times (365 days compared to at least 700 days for the other sites; see Section C.5.2), and 3) oxygen introduced into the the system may account for decreased methane production (such as at Grissom AFB, see Section 3.4).

In summary, the data from these five sites strongly indicate that anaerobic processes are effective and, quantitatively, more important than aerobic processes in achieving contaminant mass removal in groundwater.

C.5 Modeling Natural Attenuation with Aerobic and Anaerobic Reactions

GSI is overseeing the development of two natural attenuation models which will simulate both aerobic and anaerobic biodegradation reactions observed at field sites. The first model is an extension of the BIOPLUME II in-situ biodegradation model, BIOPLUME III, now being developed by Dr. Hanadi Rifai of Rice University. In addition, a simplified natural attenuation spreadsheet model, BIOSCREEN, is being developed by GSI. Both models will be validated against twelve datasets from natural attenuation sites around the country.

The BIOPLUME II model simulates natural attenuation due to oxygen only, but does not simulate the degradation due to the presence of other electron acceptors such as nitrate, sulfate, ferric iron, and carbon dioxide. In order to better simulate an aquifer's natural biodegradation potential, the BIOPLUME III AND BIOSCREEN models will be expanded to simulate the transport and uptake of anaerobic electron acceptors. In essence, the multiple electron acceptor model will track the transport of six components: contaminants, oxygen, nitrate, sulfate, ferrous iron, and methane. Aerobic biodegradation is allowed to occur first until the oxygen at a particular location is consumed, then nitrate-based degradation followed by iron and sulfate-reduction are allowed to take place. The degradative capacity due to iron reduction and methanogenic mechanisms will be estimated from the observed concentrations of ferrous iron and methane at the site.

C.5.1 Kinetics of the BIOPLUME III Model

The BIOPLUME III model is designed to be a general biodegradation code where the user will have the ability to use three different kinetic expressions: (1) first-order decay; (2) Monod dual-substrate kinetics (Rifai and Bedient, 1990); and (3) instantaneous reaction between organic contaminants and electron acceptors. A summary of each reaction model is provided below:

- **First-order decay:** This widely used model assumes the biodegradation rate is proportional to the concentration of dissolved hydrocarbon. Other factors, such as the amount of available electron acceptors, are not considered. This model is typically used by calibrating a rate constant against the observed concentration of dissolved hydrocarbon in the field. As this approach does not consider several key factors, such the amount of available electron acceptor, the long-term accuracy of these predictions for sites with limited electron acceptors is suspect. Note that first-order decay rates obtained from laboratory microcosm studies are usually not applicable to field sites because the amount of available electron acceptor that can be transported into the plume area is not the same as the amount of electron acceptor in the microcosm. Further, this model

predicts very low removal rates at low contaminant concentrations and, therefore, has been observed by GSI to over predict contaminant removal in the interior of the plume while under predicting removal at the leading edge of the plume, where dispersive mixing enhances degradation rates.

- **Monod dual-substrate kinetics:** The most complicated model, the Monod-dual substrate expression accounts for both the concentration of dissolved hydrocarbon and the concentration of available electron acceptors. In addition, two kinetic constants are employed: the maximum utilization rate that microbes can achieve when there is an excess of hydrocarbon and electron acceptor, and a half-saturation constant that describes the biodegradation rate when there is some limitation in either electron acceptor or hydrocarbon. Although this model is the most accurate, it requires the determination of these additional parameters. In addition, this model may require the longest computational time, potentially limiting its use to research projects.
- **Instantaneous reaction:** The instantaneous reaction expression is a simplification of the Monod model that assumes the biodegradation rate is dependent on the transport of electron acceptors to the plume area, and not on the maximum utilization rate of the biomass. In other words, because the mixing of hydrocarbon and electron acceptors (by dispersive mixing; for example) is generally so slow, the maximum utilization rate in the biomass is never reached. Nevertheless, the long residence times of contaminant plumes may permit the assumption of an instantaneous reaction between electron acceptor and contaminant. If the instantaneous reaction assumption can be used, relatively simple natural attenuation models can be constructed, either by selecting instantaneous reaction options in BIOPLUME III or by programming this reaction into a spreadsheet (see below).

C.5.2 Comparison of First-Order vs. Instantaneous Kinetics

Because the Monod model is difficult to use due to computation constraints, GSI evaluated the first-order decay model and the instantaneous reaction model in detail as part of the model development work performed for AFCEE. The goal was to determine the best kinetic model for each electron acceptor, or to combine the electron acceptors in some fashion to simulate the natural attenuation observed at field sites.

A simple evaluation indicates the strength and weaknesses of each approach: the first order model lumps together a number of attenuation processes but does not consider any rate limitations due to depleted electron acceptors. On the other hand, the instantaneous model incorporates the availability of electron acceptors but assumes that the biomass can consume the hydrocarbon so fast that the transport and mixing are limiting, not the biomass utilization rate. To compare the two models, three lines of evidence were evaluated.

- **Depletion of Electron Acceptors:** First, the available electron acceptors appear to be highly utilized in all of the five plumes studied. At the Bldg. 735 site at Grissom AFB, for

example, both oxygen and sulfate depletion are observed. Kinetic constraints do not appear to limit the utilization of electron acceptors, except perhaps for methanogens, even at sites with relatively fast transport rates, supporting use of the instantaneous reaction.

- **Available Reaction Time:** The second indirect line of evidence compares the maximum utilization rate observed in the laboratory to the "reaction time" available for natural attenuation in the contaminant plumes. A microcosm study conducted by Davis et al. (1994) provides a rough estimate of the maximum utilization rate when there is an excess of electron acceptor. The results of this study indicate that dissolved benzene is almost completely consumed in about 8-35 days under aerobic conditions. As expected, the anaerobic reactions were slower: approximately 80 days were required to consume most of the benzene for both sulfate reducers and methanogens. No benzene degradation was observed when nitrate was the electron acceptor, a result that has been observed by other researchers as well.

Note that these reaction times are relatively short compared to the time available for natural attenuation reactions in the field. At the Hill AFB site, for example, electron acceptors have over 365 days residence time in the plume to complete the reaction. Other sites have much longer residence times: approximately 700 days for the Hanger 10 site, 1000 days for ST-41 site, and 1500 days for the Patrick AFB site. In summary, the analysis of residence times indicates there is plenty of time to complete the anaerobic reactions in these plumes (except perhaps for methanogenic reactions), supporting use of the instantaneous reaction assumption.

- **Predictive Capability:** The final comparison of the two kinetic expressions was performed by modeling the five natural attenuation sites described above. The predictive capability of both kinetic expressions were evaluated based on their ability to reproduce the observed plume shape and observed depletion of electron acceptors and generation of metabolic by-products. In general, both models were able to reproduce the general shape of all five contaminant plumes by manipulating the input source concentration. However, preliminary results indicate that the first-order decay model under predicted the observed depletion of electron acceptors and the generation of by-products by a factor of 2 to 3. The instantaneous reaction model performed better in reproducing the observed distribution of oxygen, nitrate, ferrous iron, sulfate, and methane. This analysis supported use of the instantaneous reaction assumption.

C.5.3 Instantaneous Reaction Models: Modified BIOPLUME II Model

Because the BIOPLUME III model is still under development, two different modeling tools have been developed which use the instantaneous reaction approach: 1) a modified version of the BIOPLUME II model, and 2) the BIOSCREEN natural attenuation screening model.

To implement the instantaneous reaction assumption in modeling the contaminant plume at the Bldg. 735 site at Grissom AFB, the BIOPLUME II model was modified to incorporate all electron acceptor mechanisms into the

instantaneous reaction equation. Using an approach suggested by Wilson (1995) and Wiedemeier et al. (1994), the background concentrations of the anaerobic electron acceptors were converted to an equivalent oxygen concentration by multiplying each by the ratio of utilization factors for oxygen and the given anaerobic electron acceptor. These adjusted concentrations were then added to the observed background concentration of oxygen for input to the model (see Section 3.5). Additional work is being conducted to evaluate a hybrid instantaneous reaction/kinetic reaction model, where the hydraulic residence time of the site (or Dahmkohler number) is used to select the appropriate reaction term. Preliminary results indicate the instantaneous reaction assumption is suitable for most electron acceptors at most sites. For fast sites, such as the Hill AFB site, some type of kinetic model may be more appropriate for the less energetic reactions.

C.5.4 BIOSCREEN Spreadsheet Model

The instantaneous reaction assumption is amenable for use in simple analytical models, which can be built into commercial spreadsheet packages. Several analytical models are currently available for 2-D or 3-D analysis of contaminant transport under homogeneous, isotropic conditions, based on site-specific groundwater flow parameters and contaminant characteristics (ASTM, 1994; Wilson and Miller, 1978; Domenico and Robbins, 1985). In most analytical modeling applications, contaminant biodegradation is estimated using a first-order decay equation, with the biodecay half-life values determined from research literature or site data. However, as described above, such first-order expressions do not appear to be as accurate for describing natural attenuation processes as the instantaneous reaction assumption.

To incorporate the instantaneous reaction into a simple spreadsheet-based analytical model, a superposition method can be used. By this method, contaminant mass concentrations at any location and time within the flow field are corrected by subtracting 1 mg/L organic mass for each mg/L of degradation capacity provided by all of the available electron acceptors, in accordance with the instantaneous reaction assumption. Borden et al (1986b) concluded that this simple superposition technique was an exact replacement for more sophisticated oxygen-limited expressions, as long as the oxygen and hydrocarbon had the same transport rates (e.g., retardation factor, $R = 1$). Connor, Newell, Nevin, and Rifai (1994) revived this approach for use in spreadsheets, and compared the results to those from more sophisticated but difficult to use numerical models. They found this approach to work well, even for retardation factors greater than 1.

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In summary, biodegradation of organic contaminants in groundwater cannot be accurately characterized using a first-order decay equation because electron acceptor limitations are not considered. Rather, a more accurate prediction of biodegradation effects can be achieved by incorporating the instantaneous reaction equation into a transport model. This approach forms the basis for the BIOSCREEN natural attenuation model and will be an option in the BIOPLUME III model.

APPENDIX E BASELINE EXPOSURE ASSESSMENT PROCEDURES

Treatability Study/Focused Feasibility Study

Building 735 Site, Grissom AFB, Indiana

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E.1 INTRODUCTION

In order to perform a baseline exposure assessment for the Building 735 site, risk assessment modeling was conducted on relevant soil, air, groundwater, and surface water exposure pathways (see Figure 4.2). Chemical transport and potential exposure to human receptors was modeled along each pathway using reasonable maximum exposure assumptions (RME), site-specific monitoring data, and a variety of transport models. Using the standards in applicable EPA guidelines (see EPA reference list in Appendix A), the results were used to: i) estimate the baseline risk associated with Building 735 site and ii) calculate preliminary site-specific media cleanup levels which are protective of human health and the environment. The following paragraphs describe each exposure pathway considered, list exposure assumptions, and detail the transport models used.

E.2 GENERAL PROCEDURES

E.2.1 General Exposure Assessment Procedures

Exposure pathways are composed of three elements: source zone, transport mechanism, and receptor. The paragraphs below outline the general procedures used to calculate cleanup levels for each environmental medium at the site.

First, a target risk level was chosen for each type of constituent present at the site. Based on relevant EPA guidelines, carcinogenic target risk levels of $1.0E-6$ for Class A and B carcinogens and $1.0E-5$ for Class C carcinogens were chosen. For systemic toxicants, a target hazard quotient of 1.0 for individual constituents and a hazard index of 1.0 for cumulative effects have been employed.

Exposure assessment calculations were performed on each pathway to determine the maximum daily human intake for each constituent in milligrams of chemical per kilogram of body weight per day (mg/kg/day), averaged over the typical lifetime. These exposure calculations were based on exposure assumptions for individual receptors along each relevant exposure pathway. Maximum allowable concentrations at the point of exposure were calculated for carcinogens by multiplying daily intake by target risk and by the appropriate chemical-specific cancer slope factor (in units of kg*day/mg). Maximum allowable exposure concentrations for systemic toxicants were

calculated by multiplying daily intake by target hazard, and dividing by the appropriate chemical-specific chronic reference dose (in mg/kg/day).

Following calculation of intake doses for each constituent, dilution and attenuation factors (DAFs) were calculated based on appropriate transport mechanisms. DAFs represent the ratio of i) constituent concentrations in the source zone to ii) the predicted concentrations at the point of exposure, accounting for natural dilution and attenuation effects within the flow system. Multiplying a DAF by the allowable exposure point concentration yields a target source zone concentration which is protective of human health.

Finally, media clean-up values for each affected source media (i.e., groundwater, surface soils, and subsurface soils) were calculated for each exposure pathway by multiplying target levels at each receptor by appropriate DAF values. For media with multiple exposure pathways, the minimum (i.e., lowest) clean-up concentration was chosen as the applicable cleanup level, to be protective of all relevant receptors.

Assumed exposure parameters and default model input values were derived using best professional judgment and from the following sources, in order of priority:

- EPA Risk Assessment Guidance for Superfund (RAGS) (EPA Reference list, Appendix A)
- EPA Exposure Factors Handbook (EPA Reference list, Appendix A)
- EPA's Dermal Exposure Assessment: Principles and Applications (EPA Reference list, Appendix A)
- ASTM Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites, July, 1994.

Site-specific data used as input to the transport models described below are provided on Table 4.2, while default exposure parameters are listed on Table 4.1. Chemical-specific data are provided in Table 4.3 and Appendix E.

E.2.2 General Risk Calculation Procedures

Calculation of risk was performed by multiplying chemical intake by the appropriate toxicity criteria, for each constituent and for each pathway at Building 735 site. For all air, soil, groundwater, and surface pathways, the acceptable EPA target risk levels (i.e., $1.0E-6$ for Class A and B carcinogens and

1.0E-5 for Class C carcinogens) were used for the risk calculation. For systemic toxicants, a hazard quotient of 1.0 was used in all calculations. For constituent of both carcinogenic and toxic (i.e., Benzene), a risk level and hazard quotient were both calculated.

E.3 AIR EXPOSURE PATHWAYS

E.3.1 Surface Soils: Vapor Inhalation and Dust Ingestion (Pathway 1)

This pathway is based on ingestion of soil with inhalation of volatilized vapors and wind-borne particulates (see Figure 4.2, Pathway 1). For off-site receptors, only inhalation and wind driven transport were considered. Applicable source, transport, and receptor characteristics for this pathway are as follows:

- *Source Characteristics:* Site-specific information for the calculation of risk due to this pathway includes source area, source thickness, and soil porosity.
- *Contaminant Transport:* Transport of wind-borne vapors and particulates to off-site receptors was simulated using a conservative box model and gaussian plume dispersion algorithms. Site-specific values for width of the source area and the distance to the closest downwind receptor were used as input to the model, along with standard default values for physical parameters outlined in Appendices X.2 and X.3 of the ASTM Emergency Standard Guide for Risk-Based Corrective Action (Reference list, Appendix A). For off-site receptors, ingestion was not considered as an intake route.
- *Receptor:* Receptors in this pathway were considered to be either base personnel or construction workers located on-site, or residents located off-site (see Table 4.2).

E.3.2 Subsurface Soils: Volatilization to Ambient Air (Pathway 2)

For subsurface soils, inhalation of volatilized vapors emanating at ground surface was evaluated (see Figure 4.2, Pathway 2). This pathway was modeled the similar way as the above discussed surface soils, with soil ingestion and particulate inhalation omitted. A simple model based on the ASTM Emergency Standard Guide (Reference list, Appendix A) was developed to

convert the surface soils volatilization factor to reflect subsurface soils. This procedure was employed to assume the concern of affected soil being located at depth. As with Pathway 1, both off-site residential and on-site non-residential receptors were evaluated. Applicable source, transport, and receptor characteristics for this pathway are as follows:

- *Source Characteristics:* The risk calculation for this pathway included the following site-specific data: source area, source thickness, depth to affected soil, and soil porosity. Input values are shown on Table 4.2.
- *Constituent Transport:* Transport of wind-borne vapors and particulates to off-site receptors was simulated using a conservative box model and gaussian plume dispersion algorithms. Site-specific values for width of the source area and the distance to closest downwind receptor were used as input to the model, along with standard default values for physical parameters outlined in Appendices X.2 and X.3 of the ASTM Emergency Standard Guide for Risk-Based Corrective Action (Reference list, Appendix A). For off-site receptors, ingestion was not considered as an intake route.
- *Receptor:* Receptors in this pathway were considered to be either base personnel or construction workers located on-site, or residents located off-site (see Table 4.2).

E.4 GROUNDWATER EXPOSURE PATHWAYS

E.4.1 Soil Leaching to Groundwater (Pathway 3)

Leaching from affected soils to groundwater receptors was not evaluated, as the soils were assumed to be in equilibrium with groundwater. Therefore, the risks associated with this pathway are addressed under groundwater migration pathway discussed below.

E.4.2 Dissolved Groundwater Plume: Ingestion (Pathway 4)

This pathway was based on groundwater ingestion pathway and considers ingestion of drinking water taken from a hypothetical off-site residential water supply well (see Figure 4.2, Pathway 4). A modified BIOPLUME II groundwater solute transport model was applied to simulate movement of

the affected groundwater plume through the subsurface from the source zone to a hypothetical drinking water well, as discussed in Section 3.5. According to the results of the modified BIOPLUME II simulations, the groundwater contaminant plume is shrinking and will dissipate after 10-25 years. Therefore, the current plume area is assumed never reach the property boundary, or the surface water discharge point located 150 ft downgradient of the groundwater flow direction. Applicable source, transport, and receptor characteristics are as follows:

- *Source Characteristics*: The BTEX dissolution and desorption process was modeled by increasing the retardation factor in the model to reflect the presence of additional leachable BTEX in the saturated soils. An overall retardation factor of 47, as the retardation factor equals the ratio of dissolved BTEX mass to the total BTEX mass (dissolved BTEX + soil BTEX) was used as input to the BIOPLUME II model. Input values are shown in Table 3.1.
- *Constituent Transport*: The modified BIOPLUME II model was used to simulate advection, dispersion and natural attenuation of constituents in groundwater. The model simulates both aerobic and anaerobic biodegradation using the instantaneous reaction assumption. Site-specific values for hydraulic gradient, hydraulic conductivity, biodegradation capacity, and modified retardation factor were input to the model (see Table 3.1).
- *Receptor*: The assumed receptor was a user of a hypothetical drinking water well located at the closest residential or agricultural land-use property downgradient from the source zone. The assumed exposure parameters were based on residential land use (see Table 4.1).

E.5 SOIL EXPOSURE PATHWAY

E.5.1 Surface Soils or Sediments: Dermal Contact (Pathway 5)

For sites where exposed surface soils are affected, dermal contact exposure was also evaluated (see Figure 4.2, Pathway 5). This pathway was modeled in accordance with the EPA risk assessment guidance (EPA Reference list, Appendix A). Applicable source, transport, and receptor characteristics for this pathway are as follows:

- *Source Characteristics:* For this pathway, site-specific data was limited to the depth of affected soils and the upper-range concentrations of detected constituents.
- *Constituent Transport:* Only direct contact without transport is considered.
- *Receptor:* Receptors were assumed to be on-site construction workers without wearing OSHA specified personal safety equipment.

E.6 SURFACE WATER EXPOSURE PATHWAYS

E.6.1 Soil Leaching and Groundwater Plume Discharge to Surface Water (Pathway 6)

Soil leaching and groundwater plume discharge to surface water was not evaluated, as the soils were assumed to be in equilibrium with groundwater. Therefore, the risks associated with this pathway are addressed under groundwater plume discharge to surface water pathway discussed below.

E.6.2 Groundwater Plume Discharge to Surface Water (Pathway 7)

This pathway assumed the drainage ditch located 150 ft downgradient of leading edge of the groundwater plume serves as a hydraulic capture zone for a large portion of Building 735 site. This pathway consists of two elements: i) groundwater transport from the source zone to the drainage ditch and ii) discharge and dilution in the ditch. As mentioned in E.4.2, the BIOPLUME II model predicts that the groundwater contaminant plume is shrinking and therefore never reached the drainage ditch. Applicable source, transport, and receptor characteristics are as follows:

- *Source Characteristics* The BTEX dissolution and desorption process was modeled by increasing the retardation factor in the model to reflect the presence of additional leachable BTEX in the saturated soils. An overall retardation factor of 47, as the retardation factor equals the ratio of dissolved BTEX mass to the total BTEX mass (dissolved BTEX + soil BTEX) was used as input to the BIOPLUME II model. Input values are shown in Table 3.1.

- *Constituent Transport*: The modified BIOPLUME II model was used to simulate advection, dispersion and natural attenuation of constituents in groundwater. The model simulates anaerobic biodegradation using the instantaneous reaction assumption. Site-specific values for hydraulic gradient, hydraulic conductivity, biodegradation capacity, and modified retardation factor were input to the model (see Table 3.1).
- *Receptor*: Sources used to develop surface water criteria for this pathway were in the following order of priority: i) Indiana Water Quality Standards (Reference List, Appendix A), ii) EPA's Section 304(a) Criteria for Priority Toxic Pollutants (Reference list, Appendix A). Receptors were assumed to be base personnel or residents in recreation activities.

E.7 SUMMARY OF ANALYTICAL MODELING METHODS

Exposure analyses described in Sections E.2 - E.6 above were conducted using spreadsheet-based analytical transport models for air, and the modified BIOPLUME II solute transport model for groundwater and surface water exposure pathways. Air transport expressions employed in this study are summarized on Table E.1 attached.